SAB Ecological Processes and Effects Committee Augmented for Ballast Water Activities: Compilation of Draft Texts

This draft document is the compilation of draft texts prepared by individual subgroups of the EPA Ecological Processes and Effects Committee (EPEC), as augmented for the development of an Advisory on Ballast Water Management. This document does not represent the consensus view of the entire committee, nor has it been formatted in standard SAB report style. This draft document has been compiled solely to assist the committee in its further deliberations on the topic of ballast water management.

This document consists of six sections:

Each section of the compiled draft document is preceded by its individual table of contents.

EPA SAB Ballast Water Advisory

Section 1: Background, context, and glossary on ballast water issues

Section 1 Tables

I. Introduction

This working draft describes: (1) background on Ballast Water Advisory activities of the EPA SAB EPEC, augmented for ballast water; (2) the regulatory context within which ballast water treatment technology is developed and used; (3) a simplified glossary of key regulatory terms as they relate to the regulation or management of ballast water, now or in the near future; and (4) the objectives of ongoing, contemporaneous Science Advisory Board (SAB) and National Academy of Sciences (NAS) panels convened to examine ballast water issues.

II. Background on Ballast Water Advisory activities:

Vessel ballast water discharges are a major source of nonidigenous species introductions to marine, estuarine, and freshwater ecosystems of the United States. Ballast water discharges are regulated by EPA under authority of the Clean Water Act (CWA) and the U.S. Coast Guard under authority of the Nonindigenous Aquatic Nuisance Prevention and Control Act, as amended (NANPCA). NANPCA generally requires vessels equipped with ballast water tanks and bound for ports or places in the United States after operating beyond the U.S. Exclusive Economic Zone to conduct a mid-ocean ballast water exchange, retain their ballast water onboard, or use an alternative environmentally sound ballast water management method approved by the U.S. Coast Guard. Under the authority of the CWA, EPA's Vessel General Permit, in addition to the mid-ocean exchange, requires the flushing and exchange of ballast water by vessels in Pacific near-shore voyages and saltwater flushing of ballast water tanks that are empty or contain only un-pumpable residual ballast water.

While useful in reducing the presence of potentially invasive organisms in ballast water, ballast water exchange and saltwater flushing can have variable effectiveness and may not always be feasible due to vessel safety concerns. On August 28, 2009, the U.S. Coast Guard proposed establishing standards for concentrations of living organisms that can be discharged in vessel ballast water (74 FR 44632), and some States have established standards of their own. In addition, a number of studies and reports have been published on the status and efficacy of ballast water treatment technologies, and data collected on the efficacy of certain systems is available.

EPA's Office of Water (OW) has requested SAB review of technical documents and available data on the efficacy of ballast water treatment systems and advice on improving the performance of such systems.

III. Existing regulations for ballast water treatment

A. U.S. Federal rules

In December 2008, US EPA issued the Vessel General Permit (VGP) as authorized under the Clean Water Act (CWA). Among other things, the CWA authorizes EPA to set technology-based effluent limits. The technology based discharge limits for ballast water in EPA's current

VGP rely on "best management practices" (primarily use of ballast water exchange, or BWE) and do not include a Federal numeric discharge limit. The current VGP expires Dec. 19, 2013.

Existing US Coast Guard (USCG) rules governing ballast water as authorized under the National Invasive Species Act (NISA) also primarily rely on use of ballast water exchange. Though the exact BWE provisions are not identical, the general principle of BWE as used by EPA and USCG is very similar. In August 2009, the USCG proposed a revision to their existing rules under NISA to establish numeric concentration based limits for organisms in ballast water. That proposed rule, would initially require compliance with the Regulation D-2 standards contained in the February 2004 International Convention for the Management and Control of Ships' Ballast Water and Sediment (aka "Phase I standards") and then susbsequently require compliance with a standard 1000 times more stringent (aka "Phase II standard." The USCG has not yet finalized that proposed rulemaking, and in the meantime continues to require use of BWE.

B. Other regulatory frameworks: States and Congress

United States: Under the CWA, U.S. states have the authority to impose their own ballast water discharge standards through the CWA section 401 certification process applicable to Federally-issued "NPDES" permits such as the VGP. A number of States have exercised that authority by setting numeric limits for ballast water discharges into their waters and these numeric limits are included as a condition in the VGP. In addition, several states (e.g. California and some Great Lakes states) have enacted their own independent State laws to establish ballast water treatment standards. Thus, in practice, EPA's VGP standards establish the minimum standard (or "floor") for ballast water discharges, but States retain and have exercised their authority to set standards that are more stringent.

Congress has also considered enacting new legislation over the past several years to establish ballast water treatment standards; none of these bills have been enacted as of October 15, 2010. Discussions by states, Congress, and the USCG proposed rulemaking have included references to more stringent ballast water standards, known colloquially as "100x D-2" or "1000x D-2" referring, respectively, to standards that are two to three orders of magnitude more stringent than the existing IMO D-2 guidelines.

International standards / treaties: In the international arena, the February 2004 International Convention for the Control and Management of Ships' Ballast Water and Sediments contains concentration-based limits on organisms in ballast water as set out in Regulation D-2 of that treaty. The treaty is not yet in force internationally, however, these "D-2" concentration-based limits are in practical effect the de facto standard that international equipment manufacturers are designing their equipment to meet. .

IV. Glossary of terms and acronyms

A discussion of ballast water treatment requires a working knowledge of the basic vocabulary used in describing existing and potential regulations for ballast water management, both within the U.S. and internationally. To clarify the terms used in this draft , we provide the following annotated glossary of basic ballast water terminology. It offers a succinct definition, within the

context of their relevance to the regulation or management of ballast water, now or in the near future.

IMO*:* refers to the "International Maritime Organization." The IMO is a subsidiary body of the UN that was created by an international Convention (treaty) adopted in 1948 and which now has 169 member States. It first met in 1959 and its principal responsibility is to develop and maintain the international regulatory framework for shipping with respect to safety, environmental concerns, legal matters, technical co-operation, and maritime security. This is accomplished through a variety of international treaties negotiated under the auspices of the IMO, including the February 2004 International Convention for the Control and Management of Ships' Ballast Water and Sediments. The IMO operates primarily through a number of committees and subcommittees with specialized expertise in a range of areas, with the Marine Environment Protection Committee (MEPC) being the principal IMO committee with responsibility for environmental issues associated with shipping. For more information: http://www.imo.org/home.asp

IMO-D2: refers to Regulation D-2 of the February 2004 International Convention for the Control and Management of Ships' Ballast Water and Sediments, which contains ballast water discharge standards expressed as concentrations of organisms per unit of volume for three different organism size groupings. Although the US is not a Party to the treaty, nor has it entered into force yet internationally, the D-2 standards are in practical effect the de facto international standard that treatment equipment manufacturers are designing their equipment to meet. A table containing the IMO D-2 standards is set out in the next paragraph.

IMO D-2 / P-1 (aka USCG Phase 1)*.* These terms are sometimes used in combination because their specifications are very similar. However, to be explicit, ***IMO D-2*** is defined as shown above.

P-1/USCG/Phase 1 refers to ballast water discharge standards contained in the US Coast Guard's August 28, 2009, notice of proposed rulemaking. Because this is a proposed rulemaking that has not yet been finalized, these Phase 1 standards are not currently (i.e., as of Oct 15, 2010) legally binding. For more information, refer to 74 Federal Register 44632. The table below contains the standards as stated in IMO D-2 and in the proposed USCG Phase 1, arrayed so as to enable their direct comparison.

Table 1.1 comparing IMO D2 with USCG Proposed Phase I Standard

IMO Regulation D-2 Standard	USCG Proposed Phase 1 Standards
Discharge less than 10 viable organisms per cubic metre greater than or equal to 50 micrometres in minimum dimension	For organisms larger than 50 microns in minimum dimension: Discharge less than 10 per cubic meter of ballast water;
Discharge less than 10 viable organisms per milliliter less than 50 micrometres in minimum dimension and greater than or equal to 10 micrometres in minimum dimension	For organisms equal to or smaller than 50 microns and larger than 10 microns: Discharge less than 10 per milliliter (ml) of ballast water; and
Discharge of the indicator microbes shall not exceed the specified concentrations described in the following paragraph: Indicator microbes, as a human health standard, shall include: .1 Toxicogenic *Vibrio cholerae* (O1 and O139) with less than 1 colony forming unit (cfu) per 100 milliliters or less than 1 cfu per 1 gram (wet weight) zooplankton samples ; .2 *Escherichia coli* less than 250 cfu per 100 milliliters; .3 Intestinal Enterococci less than 100 cfu per 100 milliliters.	Indicator microorganisms must not exceed: (i) For Toxicogenic *Vibrio cholerae* (serotypes O1 and O139): A concentration of <1 colony forming unit (cfu) per 100 ml; (ii) For *Escherichia coli:* A concentration of <250 cfu per 100 ml; and (iii) For intestinal enterococci: A concentration of <100 cfu per 100 ml.

100x D-2. This phrase is a shorthand way of saying 100 times more stringent than the standards contained in IMO D-2. However, note that this terminology as commonly used is **ONLY** with respect to the two larger organism size groupings contained in IMO D-2 (i.e., it does **NOT** also mean 100 times more stringent for the D-2 indicator microorganisms). **100x D-2** has been discussed in other fora such as past Congressional bills and state requirements.

1000x D- 2. This phrase is a shorthand way of saying 1000 times more stringent than the standards contained in IMO D-2. However, this terminology as commonly used is **ONLY** refers to the two larger organism size groupings contained in IMO D-2 (i.e., it does **NOT** also mean 1000 times more stringent with respect to the D-2 indicator microorganisms). **1000x D-2** has been discussed in other fora such as the potential Phase II standards in the USCG August 2009 proposed rule or as described in state requirements.

Type approval refers to the process under which a type of equipment is tested and certified by the Flag state or its authorized representative (such as a Class society) as meeting an applicable standard specified in treaty, law or regulation. Such testing and certification is conducted on a sample piece of equipment which in all material respects is identical to the follow-on production units. In the case of ballast water treatment equipment, in the international arena the type approval tests are conducted under the "G8 Guidelines." These guidelines serve to implement procedural requirements as described in Regulation D-3(1) of the February 2004 International Convention for the Control and Management of Ships' Ballast Water and Sediments. Type approval testing (also sometimes referred to as "efficacy testing") under G8 Guidelines involves both land-based and shipboard testing according to the procedures in those Guidelines to verify the tested equipment's ability to meet the **IMO D-2** ballast water discharge standards. In the US, a domestic counterpart procedure does not yet exist for ballast water treatment equipment, but a type approval procedure was proposed as part of the Coast Guard's August 28, 2009, notice of proposed rulemaking.

G-9 approval, both "Basic Approval" *and* ***"Final Approval":*** Under Regulation D-3(2)]of the February 2004 International Convention for the Control and Management of Ships' Ballast Water and Sediments, ballast water treatment systems that make use of "active substances" (biocides) to comply with the Convention are subject to approval by the Marine Environment Protection Committee (MEPC) of the IMO with respect to health, environmental, and safety issues associated with the biocide. This review and approval is conducted under the "G9 Guidelines," which were developed by MEPC to implement the Regulation D-3(2) process. Those G9 Guidelines are available at http://www.regulations.gov/search/Regs/home.html#documentDetail?R=09000064807e890e.

Under the G9 Guidelines, laboratory or bench-scale testing is conducted in order to receive *"Basic Approval*;"in contrast, "*Final Approval* "requires testing an actual piece of equipment. In practice, although G9 approval decisions are made by MEPC, MEPC uses the services of the Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) to conduct the technical reviews and make approval or denial recommendations to MEPC. (GESAMP is a technical advisory body, established in 1969, that advises the United Nations system, including IMO, on the scientific aspects of marine environmental protection). The G-9 approval process applies only to those ballast water treatment systems that make use of biocides to comply with the Convention and this process addresses only biocide-related health, environmental, and safety issues, not the efficacy of the ballast water treatment per se. ***Type-approval*** procedures, as described above, applies to all ballast water treatment systems in order to verify the ability of the tested equipment to meet the IMO D-2 standards and ***Type-approval*** is still required for systems that have received G9 Final Approval.

IMO challenge conditions: This refers to the challenge water (influent) conditions specified in the G8 (type approval) Guidelines established by the IMO's Marine Environment Protection Committee. Those G8 guidelines are available at http://www.regulations.gov/search/Regs/home.html#documentDetail?R=09000064807e8904

The challenge water conditions are specified in the Annex to those Guidelines at paragraph 2.2.2.5 (for shipboard testing) and paragraphs 2.3.3 and 2.3.17 – 2.3.22 (for land-based testing).

ETV challenge conditions: This refers to the challenge water (influent) conditions specified in EPA's Environmental Technology Verification (ETV) draft Generic Protocol for Verification of Ballast Water Treatment Technologies, available on-line at; http://standards.nsf.org/apps/group_public/download.php/7597/Draft%20ETV%20Ballast%20Water%20Prot-v4%202.pdf. The challenge water conditions are set out in § 5.2 of that draft ETV protocol.

V. Ongoing Reviews Related to Ballast Water Issues:

There are currently two contemporaneous reviews of ballast water issues: one by SAB EPEC and one by the National Research Council (NRC). The objectives of the respective reviews can be generally summarized as:

1*) SAB EPEC, augmented for ballast water:* What is the performance of shipboard ballast water treatment systems that have available effluent testing data? What is the potential performance of shipboard systems without reliable testing data? What are the principal technological impediments or constraints to improved shipboard ballast water treatment technologies? What are the principal limitations to available treatment studies and how might these limitations be overcome in future assessment of ballast water treatment technologies?

2) NRC Panel: What are the appropriate methods to assess the risk that invasive species found in ballast water discharges will successfully establish themselves in new locations?

VI. EPA SAB EPEC Charge questions – full text

Charge question 1: *Performance of shipboard systems with available effluent testing data.*

1. a. For the shipboard systems with available test data, which have been evaluated with sufficient rigor to permit a credible assessment of performance capabilities in terms of effluent concentrations achieved (living organisms/unit of ballast water discharged or other metric)?

1. b. For those systems identified in (1a), what are the discharge standards that the available data credibly demonstrate can be reliably achieved (e.g., any or all of the standards shown in Table 1 of the White Paper? Furthermore, do data indicate that certain systems (as tested) will not be able to reliably reach any or all of the discharge standards shown in that table?

1. c. For those systems identified in (1a), if any of the system tests detected "no living organisms" in any or all of their replicates, is it reasonable to assume the systems are able to reliably meet or closely approach a "no living organism" standard or other standards identified in Table 1 of the White Paper, based on their engineering design and treatment processes?

Charge question 2: *Potential performance of shipboard systems without reliable testing data.*

2. Based on engineering design and treatment processes used, and shipboard conditions/constraints, what types of ballast water treatment systems (which may include any or all the systems listed in Table 4 of the White Paper) can reasonably be expected to reliably achieve any of the standards shown in Table 1 of the White Paper, and if so, by what dates? Based on engineering design and treatment processes used, are there systems which conceptually would have difficulty meeting any or all of the discharge standards in Table 1 of the White Paper?

Charge question 3: System development.

3 a. For those systems identified in questions 1 a. and 2, are there reasonable changes or additions to their treatment processes which can be made to the systems to improve performance?

3 b. What are the principal technological constraints or other impediments to the development of ballast water treatment technologies for use onboard vessels to reliably meet any or all of the discharge standards presented in Table 1 of the White Paper and what recommendations does the SAB have for addressing these impediments/constraints? Are these impediments more significant for certain size classes or types of organisms (e.g., zooplankton versus viruses)? Can currently available treatment processes reliably achieve sterilization (no living organisms or viable viruses) of ballast water onboard vessels or, at a minimum, achieve zero or near zero discharge for certain organism size classes or types?

4. What are the principal limitations of the available studies and reports on the status of ballast water treatment technologies and system performance and how can these limitations be overcome or corrected in future assessments of the availability of technology for treating ballast water onboard vessels?

EPA SAB Ballast Water Advisory

Subgroup 7

Section 2: – Statistics and interpretation

Section 2 Figures

Section 2 Tables:

Abstract

The ways in which statistical interpretations influence ballast water testing were considered, specifically how to quantitatively assess the confidence of test results obtained from count data of low numbers of organisms. Large volumes of water are required to evaluate, in particular, the $\geq$ 50 μm (zooplankton) size class of the IMO/P-I performance standard. Assessment of the uncertainty in test results requires an accounting of the spatial nature of the distribution of zooplankton in the sampled volume of water. To that end, two distributions were considered, the Poisson and negative binomial distributions. After considering empirical data and theoretical arguments, the Poisson distribution was determined to be appropriate for analyzing data from living organisms in treated ballast water. Further, the statistical requirements and difficulties in sampling large volumes of water to find few living organisms were examined, and it was concluded that The IMO/P-I performance standards are achievable at present. Determining whether water is compliant with a standard 1000x more stringent than the IMO/P-I performance standard, however, was deemed impracticable, due to the logistics of collecting, reducing, and counting organisms in the large volumes of water required for analysis. A standard 10x more stringent may be possible, although it was evaluated as very unlikely—for the reasons mentioned above—that a standard 100x more stringent can be achieved. Finally, it was noted that statistical conclusions are always accompanied by an associated error probability; thus, "100% certainty" is not statistically possible.

Introduction

The goal of this section is to present key aspects of statistical interpretations that are most relevant to the operational conditions in which ballast water is tested. These conditions include the need to sample large volumes of water for the size class of organisms $\geq$ 50 μm in minimum dimension (nominally zooplankton), in particular, of the IMO/P-I performance standard, and to apply statistical methods that can quantitatively assess the confidence of test results obtained from count data of low numbers of organisms. Note these discussions pertain to land-based and shipboard testing to determine compliance with a given performance standard; gross non-compliance (e.g., exceedance of a standard by orders of magnitude) is not discussed here.

Credible testing to determine compliance with any standard for effectiveness of ballast water management systems requires the following process. First, large volumes of water must be collected and filtered in some way to remove organisms and place them into a manageable volume. The volume of ballast water carried by commercial ships spans a few thousand m^3 to greater than 100,000 m^3. The volume of water that must be sampled following treatment is a small fraction relative to the total volume in a ballast tank or ship, but, nonetheless, a large volume must be filtered to determine the number of live zooplankton. This size class has the lowest concentration threshold—organisms per m^3 vs. organisms per mL—and represents the most challenging size class in terms of sampling. The required sample volumes for zooplankton, which are determined by a number of factors, are in the range of five to tens of m^3; the latter approximates the volume of a city bus. Subsamples of the concentrated volume are analyzed for *living* plankton, as all standards are based on the number of organisms surviving the treatment method. Once these counts are in hand, how reliably they portray conditions in the ballast water discharge must be determined. To complete this task, the live organism counts are analyzed using statistical methods to assess the uncertainty associated with the counts.

Assessing uncertainty in test results requires accounting for the spatial nature of the distribution of zooplankton in the sampled volume of water. Different probability distributions apply depending upon whether zooplankton are randomly distributed throughout a sample or are aggregated. Hence, much of this section is devoted to demonstrating how use of appropriate probability distributions can characterize the level of reliability in taking the important inferential step from observing actual zooplankton counts to determining whether a stated standard has been met.

Ascertaining in a Rigorous Manner Whether Ballast Water Standards are Met —The Statistics of Sampling

With regard to detecting whether or not treated ballast water meets a stated standard in terms of the density of viable zooplankton in a ship's ballast water, "zero detectable discharge" initially seems a very desirable standard to achieve (see also the response to charge question 1c). However, without a well-defined, rigorous protocol based upon probability sampling, any standard, no matter how stringent, will be difficult to assess and defend. Furthermore, it will be impossible to compare the effectiveness of different BWMSs without rigorous protocols. In order to outline what a sampling scheme might entail, and what sorts of information it would yield, it is necessary to investigate the probabilistic characteristics of plankton in ballast water (BW).

In considering concentrations that approach the IMO/P-I performance standard (or a more stringent standard), plankton can have one of two spatial characteristics: they can be randomly dispersed or clumped (aggregated) (as discussed in Lee et al., 2010). Because any sampling protocol is a function of the plankton's spatial distribution, it is critical to understand the distribution in the tank and discharge pipe and then sample accordingly. For randomly distributed plankton, the Poisson distribution can be used to estimate probabilities and conduct statistical power analyses (the probability that the sampling will find a ship out of compliance when that is the case). For concentrations that are spatially aggregated, the negative binomial distribution is appropriate as the underlying statistical model. First, we consider the Poisson distribution and its relevance to ballast water sampling.

A. The Poisson distribution

The Poisson distribution has the property that its variance is equal to its mean, resulting in an increase in variability at higher densities. Since the Poisson distribution pools the data to improve measurement precision, sample replication is unnecessary if samples are continuously taken on a time-averaged basis. Assuming a given concentration, one can calculate the volume needed in order to guarantee a stated probability of finding at least a single plankter in a sample of that volume. Note that an underlying assumption is that organisms are randomly distributed – but see the section on spatially aggregated populations.

A major challenge of sampling at low organism concentrations is many samples will detect zero organisms. This can result in an estimated concentration of zero, and impractically large volumes must be sampled and excellent detection techniques must be used to enable detection of organisms in low abundance (Fig. 1). Consider the following examples from Lee et al. (2010): from the Poisson distribution, if 1 m^3 of ballast water was sampled from a discharge that had a concentration of 10 organisms m^{-3}, about 95% of the samples would contain 4-17 organisms m^{-3}. As the concentration of organisms decreases, the frequency distribution becomes increasingly skewed, and there is a high probability of obtaining a sample with zero organisms. Thus, if the sample concentration is 1 organism m^{-3}, the probability of a 1 m^3 sample containing zero organisms is 36.8%. If the sample concentration is only 0.01 organism m^{-3}, or 1 organism in 100 cubic meters of ballast water, the probability of obtaining a sample with zero organisms is ~99%. Furthermore,

> "If a small volume is used to evaluate whether the discharge meets a standard, the sample may contain zero detectable organisms, but the true concentration of organisms may be quite high….For example, even with a relatively high concentration of 100 organisms m^{-3}, only about 10% of 1-L samples will contain one or more organisms. Furthermore, even if zero organisms are detected in a 1-L sample, the upper possible concentration, based on a 95% confidence interval, is about 3,000 organisms m^{-3}….The general point is that more organisms may be released in ballast discharge using a stringent standard paired with a poor sampling protocol than a more lenient standard paired with a stringent sampling protocol" (Lee et al. 2010, p.72).

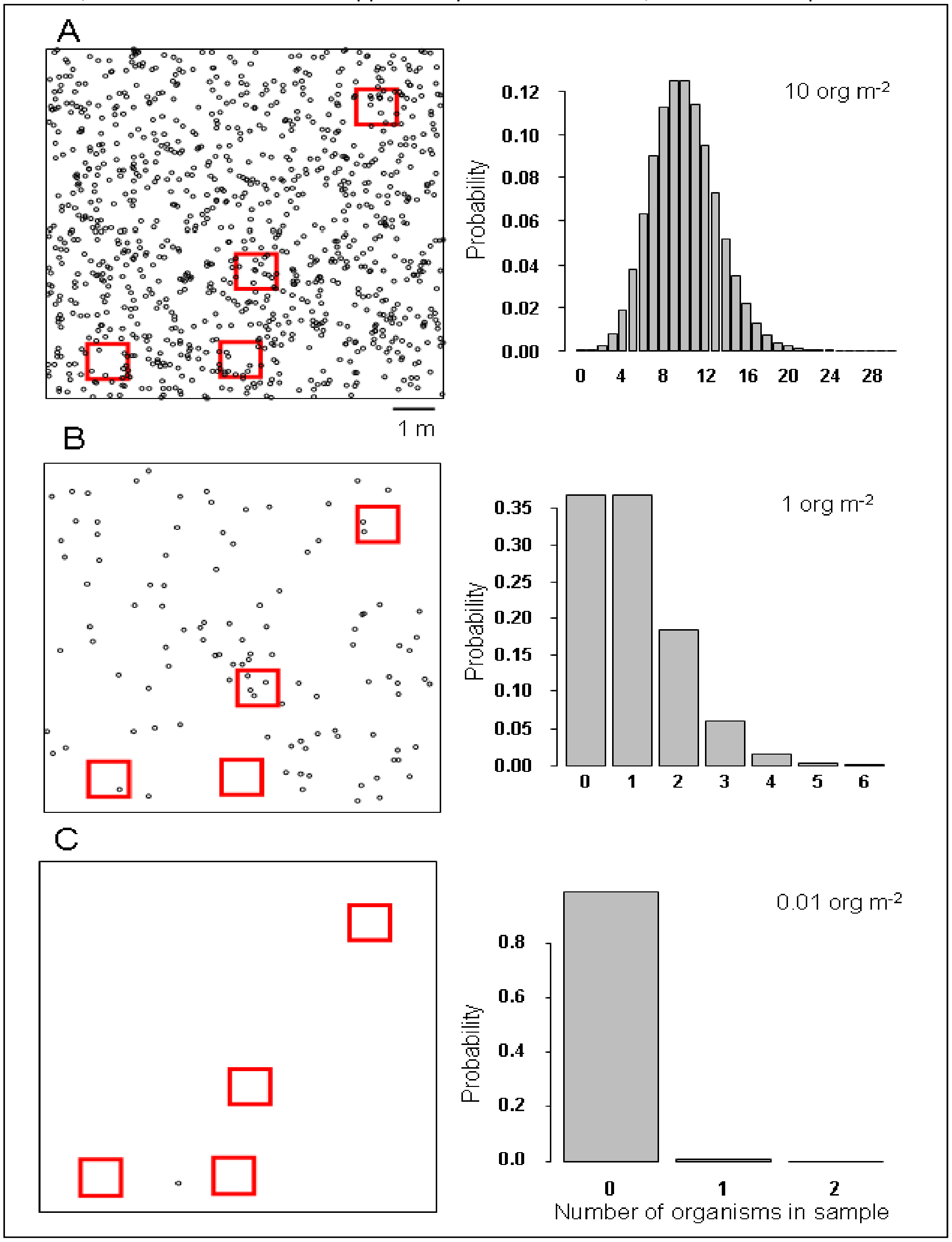

Figure 2.1. Illustration of the need to sample very large volumes to detect low concentrations of organisms present, assuming random distribution: Probability distributions for random samples of 1 m^2 for a randomly distributed population with 10 (A), 1 (B), or 0.01 (C) organisms m^{-2}. Red squares represent random samples. The data are displayed in terms of area with units of m^2, but the probabilities are the same for volumes. Plots on the right indicate the probability that a 1 m^2 sample will contain a given number of organisms. At low concentrations, the concentration of organisms is likely to be estimated as 0 organisms m^{-2}, unless very large volumes are sampled. From Lee et al. (2010), with permission.

Both the IMO G-2 guidelines and the EPA Environmental Technology Verification (ETV) Generic Protocol for the Verification of Ballast Water Treatment Technology stipulate that biological samples should be continuously acquired on a time-averaged basis from a sampling port positioned in fully turbulent flow (IMO, 2008; EPA, 2010) and are thus representative of the entire volume to be sampled. It has been argued that organism abundance in BWMS testing can be statistically represented by the Poisson distribution, and, therefore, the cumulative or total count is the key test statistic (Lemieux et al., 2008). A Chi-square distribution can also be used to approximate confidence intervals. However, experimental validation must be obtained to ensure that testing organizations can accomplish detection of live organisms with quantified uncertainty (see Section 5. II. C. B, on viability).

The available methodologies for testing compliance with the IMO standards for zooplankton and organisms ≥ 10 µm and > 50 µm (nominally protists, e.g., phytoplankton and protozoans) are at or near the analytic detection limits. The following example from the ETV illustrates the problem (EPA, 2010): if the desired minimum precision in quantifying organisms ≥ 50 µm is that the upper bound of the Chi-square statistic should not exceed twice the observed mean (which corresponds to a coefficient of variation of 40%), then ***if six or fewer*** organisms are counted, the upper bound of the 95% CI for the volume sampled does not exceed the IMO/P-I performance standard for zooplankton (i.e., < 10 viable individuals m^{-3}):

Coefficient of variation (CV) = standard deviation (SD) divided by the mean (M).
For the Poisson distribution, the variance (V) = SD^2 = M.
Substituting the critical value of the mean, 6: CV = $6^{1/2}/6 \approx 40\%$.

The volume needed to find and quantify six organisms per m^3 depends on the whole-water sample volume, the concentration factor, and the number of subsamples examined. Very large sample volumes (10s of m^3) are required to quantify viable zooplankton (assuming 20 mL of the concentrated sample is analyzed), and each sample must be concentrated down to a manageable volume (concentrating 3 m^3 to 1 L would yield a concentration factor of 3,000). Based on the Poisson distribution for a 95% confidence interval (CI) from the Chi-square distribution, 30 m^3 (30,000 L) must be sampled in order to find and count <10 organisms m^{-3} with the desired level of precision. The total sample volume can be reduced if the concentration factor is increased (and the same subsample volume analyzed), if the CI is also lowered (e.g., from 95% to 90%) or the subsample volume analyzed is increased (e.g., from 20 mL to 40 mL).

The ETV Protocol provides examples of the sample size needed to provide the level of precision needed to achieve a 95% upper confidence limit that is no more than twice the observed mean and does not exceed the targeted concentration (Tables 1 and 2). If the subsample volume analyzed is increased, then validation experiments should be conducted to ensure that counting accuracy is acceptably high. The problem is exacerbated for zooplankton because they are sparse compared to organisms in the next smaller size class, ≥ 10 to < 50 µm (protists). The Poisson distribution assumption still applies to the smaller size class, and the ETV Protocol provides examples with a more stringent level of precision than is used for the larger size class (Table 2).

Table 2.1 Sample volume of treated ballast water required relative to treatment standards for organisms ≥ 50 µm, assuming that the desired level of precision of the estimated density is set at the 95% confidence interval of the Poisson distribution (= twice the observed mean and not greater than the standard limit). These are the required whole-water sample volumes that must be concentrated to 1 L as a function of N, the number of 20 1-mL subsamples analyzed. Reprinted with permission from U.S., EPA 2010.

	N = 1	3	5
Concentration (individuals m^{-3})	Sample Volume Required (m^3)		
0.01	60,000	20,000	12,000
0.1	6,000	2,000	1,200
1	600	200	120
10	6	20	12

Table 2.2 Sample volume of treated ballast water required relative to treatment standards for organisms ≥ 10 µm and < 50 µm, assuming that the desired level of precision is set at a CV of < 10%. These are the required whole-water sample volumes that must be concentrated to 1 L as a function of N, the number of 1-mL subsamples analyzed. Reprinted with permission from U.S. EPA, 2010.

	N = 2	3	4
Concentration (individuals mL^{-1})	Sample Volume Required $(L)^2$		
0.01	6,000	4,000	3,000
0.1	600	400	300
1	60	40	30
10	6	4	3

Accuracy and precision in sparse samples following a Poisson distribution

A series of laboratory experiments was conducted to assess the accuracy and precision of enumerating zooplankton and protists at a variety of densities (Lemieux et al. 2008). Inert, 10-µm standardized microbeads at densities of 1, 5, 10, 50, 100, 500, and 1,000 beads per mL of artificial seawater represented phytoplankton, and 150-µm beads at 10, 30, and 60 beads per 500 mL represented zooplankton. Such inert, standardized polymer beads were used rather than organisms to eliminate any potential bias, and artificial rather than natural seawater was used to avoid inclusion of various organic particles (e.g., detritus) that could interact with the beads and confound interpretations.

At each bead density, the percent difference of the observed mean from the expected mean indicated counting accuracy, and the CV indicated the level of precision. Benchmarks for acceptable accuracy and precision were established at a percent difference of 10% and a CV of 0.2 (20%), respectively. For the "phytoplankton" beads, the 50-1,000 ml^{-1} concentrations were not significantly different, with acceptable accuracy and precision below the 10% and 20% benchmarks, respectively. Unfortunately, however, analysis of the "zooplankton" bead populations at all densities showed poor precision, with CVs well above 20%.

From this work, Lemieux et al. (2010) recommended that samples for analysis of the protists size class (≥ 10 µm and < 50 µm) should be concentrated by at least a factor of five and that at least four replicate chambers (e.g., Sedgwick Rafter slides) should be counted for acceptable accuracy and precision, including evaluation of at least 10 random rows (from a total of 20) of the counting chamber. Importantly, for the zooplankton size class (≥ 50 µm) size class, Lemieux et al. (2008) deemed the ETV protocol recommendations for sample sizes as inadequate to achieve acceptable precision. The data from these microbead experiments indicated, instead, that this size class requires a sample size of greater than 6 m^3, concentrated to 1 L (i.e., by a factor of 6,000), and analysis of at least 450 1-mL aliquots, as CVs at the highest volumes were > 20%. Lemieux et al. (2008) also noted that these laboratory trials represented a "best case" situation because the study was conducted under simplified, "ideal" conditions rather than with natural organism assemblages in natural seawater.

Overall, these data demonstrate that at present, the IMO G8 guidance for zooplankton at acceptable precision is achievable but with expenditure of great effort using available methodologies. Stricter standards cannot be practically assessed with available methodologies.

Using the Poisson distribution over a series of ballast water tests

When concentrations are close to the performance standard, a single sample may require too large a volume of water to be logistically feasible. In that case, complete, continuous, time-integrated sampling (with the entire volume analyzed) and combining samples across multiple trials can improve resolution while maintaining statistical validity. To that end, Miller et al. (2010) applied statistical modeling (based on the Poisson distribution) to a range of sample volumes and plankton concentrations. They calculated the statistical power of various sample volume and zooplankton concentration combinations to differentiate various zooplankton concentrations from the proposed standard of < 10 m^{-3}.

Their study involved a two-stage sampling approach. Stage I checked compliance based on a single sample, which was expected to be effective when the degree of noncompliance was large. Stage 2 combined several samples to improve discrimination (1) when concentrations are close to the performance standard, or (2) when a large volume single-trial sample would be logistically problematic, or both. The Stage 2 approach takes advantage of the fact that the sum of several Poisson random variables is still a Poisson distribution, and is thus called the "summed Poisson method". Stage 2 also compared the summed Poisson approach to power calculations using standard t-tests, the nonparametric Wilcoxon Signed Rank test (WSRT), and a binomial test, all well-known statistical techniques. The summed Poisson approach had more statistical power relative to the other three statistical methods. Not surprisingly, as noncompliant concentrations approach the performance standard, sampling effort required to detect differences in concentration increases.

The major finding from Miller et al. (2010) is that three trials of time-integrated sampling of 7 m^3 (and analyzing the entire concentrated sample from the 21 m^3) from a ship's BW discharge can theoretically result in 80% or higher probability of detecting noncompliant discharge concentrations of 12 vs. 10 live organisms m^{-3} (Miller et al., 2010). Thus, pooling volumes from separate trials will allow lower concentrations to be differentiated from the performance standard, although the practicability and economic costs of doing so have not been evaluated. Moreover, the practical limits of increased statistical sample sizes may already tax the capabilities of well-engineered ballast water test facilities

Additional challenges of sampling large volumes

As outlined in Lee et al. (2010), the detection of organisms at very low concentrations, required to assess performance and compliance, is a major practical and statistical challenge, partly because of the inherent stochasticity of sampling. Due to random chance, the number of organisms in multiple samples taken from the same population will vary. In addition, very large volumes of water must be sampled in order to accurately estimate the organism densities. Other considerations include:

First, statistical approaches in assessing treatment performance generally rest upon the premise that the samples realistically represent the actual concentrations of organisms discharged which, in turn, is based on two assumptions: random distribution of organisms in ballast tanks and discharge water, and no human or equipment error that would lead to failure to detect organisms in a sampled volume. Neither assumption will be true all of the time. Human and equipment errors will occur and organisms are typically "patchy" or non-random in the water column of a tank or the stream of a large-volume discharge (Murphy et al. 2002, U.S. EPA 2010). The assumptions are made for practical reasons; if appropriate quality control and assurance were used in collecting the data, then human error and equipment malfunction would have been accounted for. Regarding the second assumption, data are usually lacking to estimate aggregation in ballast water.

Second, the logistics of managing large sampling containers, sample transport costs (since samples usually are not processed aboard ship), analytical supplies, and personnel time would make it impractical to process all of the volume of even one 100 m^3 sample, much less multiple samples, especially in Type Approval of BWMSs, when multiple, successful tests are required. Logistic of sampling and analysis become more intractable with efforts to assess compliance with IMO standards for microorganisms.

Lee et al. (2010) calculated the probability of finding one or more organisms in a sample as $1\text{-}e^{cv}$ (1 minus the probability of finding no organisms) for a series of organism concentrations and sample volumes, where e ≡ the natural log, c ≡ the true concentration of organisms, and v ≡ the sample volume (Table 3). They used the following assumptions:

(i) Performance standards are for the concentration of organisms in the ballast discharge (rather than the maximum number of organisms), so that the purpose of sampling is to estimate the "true" concentration of organisms in the discharge, referred to as average-based sampling;

(ii) The organisms are randomly distributed and therefore amenable to modeling with the Poisson distribution, as above;

(iii) All organisms are counted, with no human or instrumentation errors, so that any variation among samples for a given population (species) is from the natural stochasticity of sampling;

(iv) The sample volume is calculated from the total volume of ballast water filtered (concentrated) and the filtrate volume that is subsampled. For example, following Lemieux et al. (2008): 100 m^3 of ballast water is filtered through a net to retain the ≥ 50 µm size class; the organisms are rinsed from the net, collected, and diluted up to 1 L of water to give a concentration factor of 100,000:1. The organisms from 20 1-mL subsamples are counted: Total sample volume = 20 mL subsamples/1000 mL concentrated sample x 100 m^3 ballast water filtered = 2 m^3.

Table 2.3. Probability of detecting ≥ 1 organism for various sample volumes (100 mL to 300 m^3) and ballast water concentrations (0 to 100 organisms m^{-3}). Gray boxes indicate probabilities of detection ≥ 0.95. Reprinted with permission from Lee et al. (2010).

	True concentration (organisms per m^3)						
Sample volume, m^3	**0**	**0.001**	**0.01**	**0.1**	**1**	**10**	**100**
0.0001 (100 mL)	0	<0.001	<0.001	<0.001	<0.001	0.001	0.01
0.001 (1 L)	0	<0.001	<0.001	<0.001	0.001	0.01	0.095
0.01 (10 L)	0	<0.001	<0.001	0.001	0.01	0.095	0.632
0.1 (100 L)	0	<0.001	0.001	0.01	0.095	0.632	>0.99
1	0	0.001	0.01	0.095	0.632	>0.99	>0.99
5	0	0.005	0.049	0.393	>0.99	>0.99	>0.99
10	0	0.010	0.095	0.632	>0.99	>0.99	>0.99
25	0	0.025	0.221	0.918	>0.99	>0.99	>0.99
50	0	0.049	0.393	>0.99	>0.99	>0.99	>0.99
100	0	0.095	0.632	>0.99	>0.99	>0.99	>0.99
300	0	0.259	0.950	>0.99	>0.99	>0.99	>0.99

As Table 2.3 illustrates, about 100 L of ballast must be sampled to have a 95% probability of detecting at least 1 organism when the true concentration is 100 organisms per m^3. When small sample volumes are collected, the probability of detecting an organism is low even at relatively high organism concentrations; for example, organisms will be detected in fewer than 10% of subsamples if a 1-L sample is taken and the "true" concentration is 100 organisms m^{-3}. This

analysis also illustrates that when no organisms are detected from a ~small sample, the true concentration in the ballast tank may be large – it depends on the sample volume collected.

Lee et al. (2010) then estimated the upper possible concentration (UPC, upper 95% CI) of organisms actually present in ballast water from the number of organisms in a sample volume (range, 100 mL to 100 m^3), based on the Poisson distribution. As Table 4 shows, 0 organisms detected in 1 m^3 of sample could correspond to a true concentration of organisms in the ballast tank of up to ~3.7 organisms m^{-3}. The error is much larger for a small sample volume of 1 L; 0 organisms detected could correspond to a true concentration of ~3,700 organisms m^{-3}.

Table 2.4. Upper possible concentration (UPC) of organisms based on one and two tailed 95% exact confidence intervals when zero organisms are detected in a range of sample volumes. Reprinted with permission from Lee et al. (2010).

	Upper possible concentration, org m^{-3}	
Sample volume, m^3	**one-tailed**	**two-tailed**
0.0001 m^3 (100 mL)	29,960	36,890
0.001 m^3 (1 L)	2,996	3,689
0.01 m^3 (10 L)	299.6	368.9
0.1 m^3 (100 L)	29.96	36.89
0.5 m^3 (500 L)	5.992	7.378
1 m^3	2.996	3.689
10 m^3	0.300	0.369
100 m^3	0.030	0.037

Third, in the above analyses, the true organism concentrations are known. The goal in sampling unknown concentrations of organisms in ballast water is to accurately assess whether a given ballast water treatment system produces treated water with true organism concentrations that pass or fail a set performance standard. Inherent stochasticity of sampling may result in an indeterminate category, as well, and the probability of obtaining an indeterminate evaluation increases with decreasing sample volume and increasing stringency of the ballast water standard (Figure 2). Based on this analysis, it would be necessary to sample ~0.4 m^3 of ballast water to determine whether the IMO standard of < 10 organisms m^{-3} was met (Figure 2B).

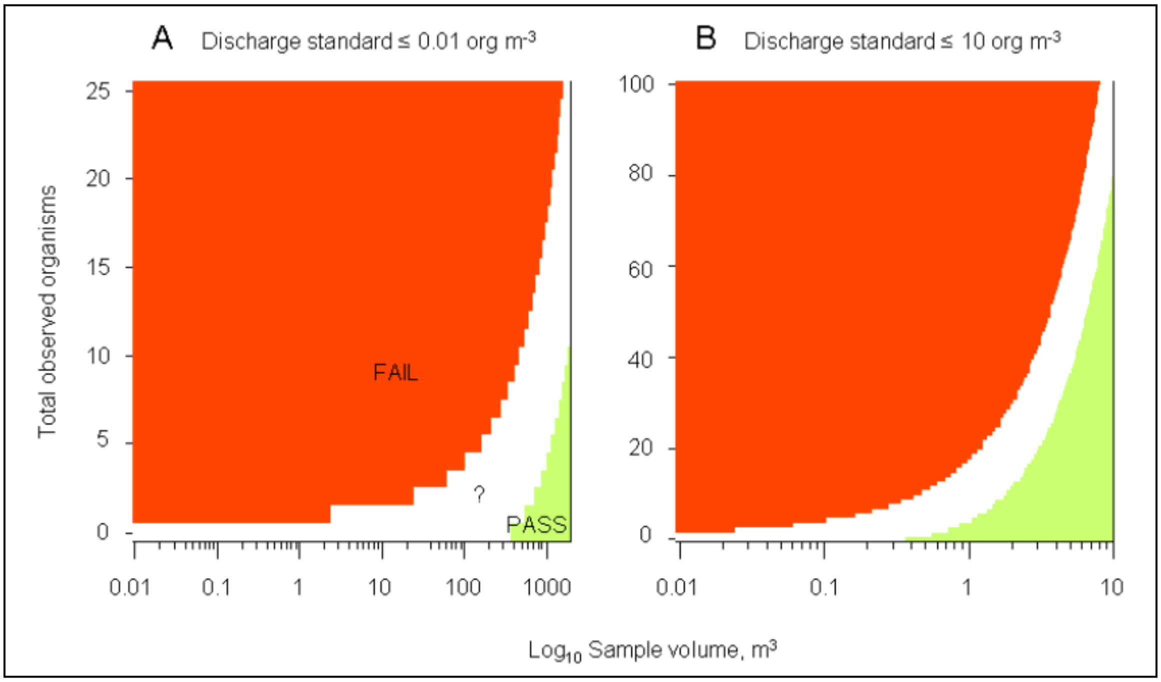

Figure 2.2 Determining whether ballast water discharge exceeds or meets a performance standard of < 0.01 (A) and <10 (B) organisms m-3 (note: axes have different scales). Red regions indicate total organism counts that exceed the standard. Green regions indicate total organism counts that meet the standard. White regions indicate indeterminate results; counts in this region do not pass or fail inspection based on two-tailed 95% confidence intervals. Reprinted with permission from Lee et al. (2010).

Spatially Aggregated Populations—Negative Binomial Distributions

If organisms are aggregated (i.e., coming from clumped or contagious populations) rather than randomly distributed in the ballast tank, a different statistical approach is required. For aggregated populations, the variance exceeds the mean (negative binomial distribution, $\sigma^2 > \mu$); thus, as the variance increases, the number of organisms in a random sample is increasingly unpredictable. Because it is more difficult to accurately estimate the true concentration, more intensive sampling is required. Lee et al. (2010) recommend use of the negative binomial distribution to model aggregated populations. This distribution can be used to predict the probability of finding a certain number of organisms in a sample. It is defined by the mean (μ) and the dispersion or size parameter ($\theta = \mu^2/(\sigma^2 - \mu)$); the smaller the dispersion parameter, the more aggregated the population.

The problem of having to sample multiple subsamples from large volumes to accurately assess low densities of organisms is compounded by aggregated distributions (Fig. 3). In the comparison given in Lee et al. (2010), for a randomly distributed population with a true concentration of 1 organism m^{-3}, ~37% of the subsamples from a 1 m^3 sample of treated ballast water would contain zero organisms. For an aggregated population with a dispersion parameter of 0.1, however, ~79% of the subsamples would contain zero organisms (Fig. 3). The probability of samples containing large numbers of organisms relative to the true concentration also increases. Thus, large numbers of subsamples from large sample volumes must be taken to account for aggregated populations; otherwise, there will be a high probability that the concentration estimates from sample analyses will be either much lower or much higher than the true concentration.

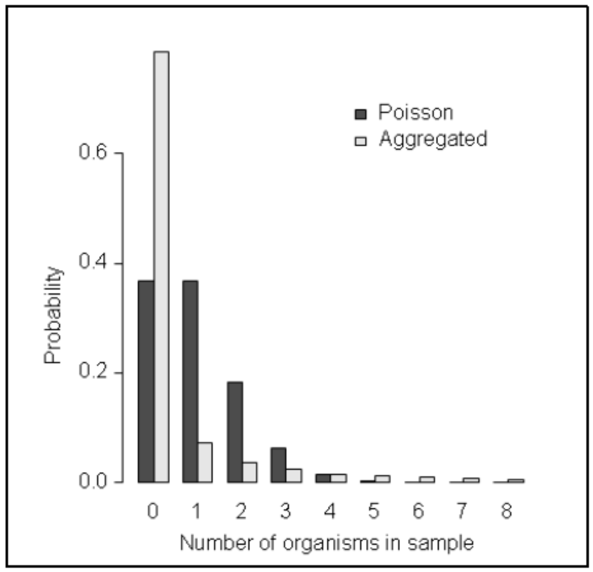

Figure 2.3. Comparison of sample probabilities from a randomly distributed population (Poisson distribution) vs. an aggregated population with a dispersion parameter of 0.1 (negative binomial distribution) for a sample volume of 1 m^3 and concentration of 1 organism m^{-3}. For low organism numbers (3 or fewer m^{-3}), the probability that a sample will contain zero organisms tends to be much greater for the aggregated population. Reprinted with permission from Lee et al. (2010).

Determination of whether a population is aggregated is complicated, since the scale of the aggregation pattern in comparison to the size of the sampling unit controls estimates of aggregation (Fig. 4). If organisms form clumps that are randomly distributed, the population may be highly aggregated, but in a small sample volume containing 0 or 1 organisms, the population will appear randomly distributed or only slightly aggregated. With increasing sample volume, the variance in the number of organisms increases in comparison to the mean, and maximum variance is encountered when the sample volume is equal to the volume of a single cluster of organisms (Elliott 1971). For larger sample volumes, a sample unit will include several clusters, so the variance decreases in comparison to the mean and the observations will approach a Poisson distribution. Lee et al. (2010) recommend the Taylor power law (Taylor 1961) as an alternative to the negative binomial, because it can accommodate a wider range of aggregated distributions than the negative binomial.

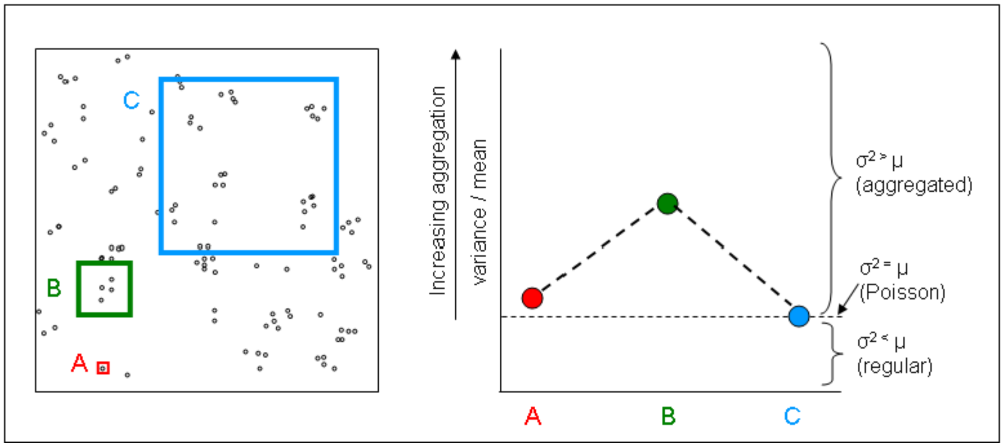

Figure 2.4. Theoretical example of how the apparent aggregation in the population will differ based on the scale of aggregation relative to the size of the sample unit. Green region ≡ acceptable counts; red region ≡ unacceptable counts; white region ≡ indeterminate result (ambiguous – may be considered as unacceptable if a high degree of confidence is needed). From Lee et al. (2010).

Overall, possibility for and degree of aggregation represent major challenges in sampling sufficiently large volumes of ballast water to determine whether a given ballast water treatment system passes or fails to meet standards more stringent than the present IMO guidelines, even if the true concentrations of organisms are 10- to 1,000-fold higher than the performance standard. This remains a major problem in quantifying many phytoplankton, but becomes less of a problem with very small organisms that have a tendency to clump but are effectively counted as colonies and not individuals, such as bacteria. Furthermore, in Lemieux et al. (2008), data from phytoplankton at various concentrations were analyzed and found to adhere to a Poisson distribution. The flasks of microbeads were well mixed, as would be samples of ballast water collected from the sample ports and collected to be representative of the entire volume sampled (i.e., over the entire discharge operation of the tank). Those data lend support to using the Poisson distribution to analyzed ballast water samples. Considering compliance issues, we support Lee et al.'s (2010) recommendation that the quality control needed to assure that treatment systems adequately minimize organism concentrations "may best be achieved through rigorous type-approval of ballast water treatment systems in controlled testing facilities, rather than from after-the-fact compliance shipboard sampling."

Interactive Effects

A final consideration regarding statistical analysis concern the potential for covariance, or interactive effects among environmental conditions – for example, a treatment system may perform well under high-temperature or high-biomass conditions, but not both (Ruiz et al., 1996). To address this problem, covariate measurements should be addressed in experiments, and treatment evaluations should consider the potential for interactions and target tests of especially challenging combinations.

Certainty of Results

It is necessary to keep in mind that as with all statements that are based upon statistical sampling, there is always a stated non-zero error probability (e.g., 0.1%, 1%, 5%) associated with a particular statistical conclusion used to meet a regulatory standard. Thus, one can never claim to be 100% certain that, for example, the concentrations of live organisms ≥ 50 μm is below (for example) 10 m^{-3}. More appropriate to statements about meeting a regulatory standard is the notion of *reasonable scientific certainty*. Based on available data (section xx—the first charge question), we conclude with *reasonable scientific certainty* that several BWMSs can reliably perform to the IMO D-2 and USCG proposed Phase I performance standard. However, current BWMSs are unlikely to ever meet 100x D-2 or 1000x D-2, and complete sterilization is simply not possible. Furthermore, current sampling and analytical methods are not adequate to allow for the resolution—with reasonable scientific and statistical certainty—that stricter standards for ballast water discharge would require.

Conclusions

- Rigorous statistical sampling protocols (including consideration of the spatial distribution of plankton in ballast water) and subsequent statistical analysis are required in order to assess whether a BWMS meets desired performance standards.

- Detecting organisms in low abundance is a difficult problem, requiring very large volumes of water to be sampled, especially for the zooplankton size class.

- The sample volumes that must be concentrated are a function of the targeted concentration, the performance standard, and the desired level of confidence (e.g., 95%, which is used most often in ecological investigations).

- The Poisson distribution is recommended as the model for statistical analysis of treated water samples.

- Available methodologies to test IMO/P-I compliance are presently at or near analytic detection limits. Improved methodologies will be required in order to increase detection limits.

- The IMO/P-I performance standards are achievable at present based on land-based and shipboard testing approaches. Due to the logistics of collecting, reducing, and counting organisms, particularly zooplankton, within the very large volumes of water required to achieve a standard 1000x more stringent than the IMO/P-I performance standard, a 1000x more stringent standard is impracticable. A standard 10x more stringent may be possible, but it seems very unlikely—for the reasons mentioned above—that a 100x more stringent standard can be achieved.

- Statistical conclusions at a stated confidence level always have an associated error probability; thus, "100% certainty" is not statistically possible.

EPA SAB Ballast Water Advisory
Subgroup 1

Section 3. Draft response to charge questions 1 and 2: Performance of shipboard systems with available effluent testing data

I. Introduction and charge questions:

This section responds to Charge Questions 1 and 2 (and their subsidiary questions) which focus on the documented and anticipated performance of existing shipboard ballast water treatment technologies. These questions are:
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Charge question 1: Performance of shipboard systems with available effluent testing data

a. For the shipboard systems with available test data, which have been evaluated with sufficient rigor to permit a credible assessment of performance capabilities in terms of effluent concentrations achieved (living organisms/unit of ballast water discharged or other metric)?

b. For those systems identified in (1a), what are the discharge standards that the available data credibly demonstrate can be reliably achieved (e.g., any or all of the standards shown in

Table 1 of the White Paper? Furthermore, do data indicate that certain systems (as tested) will not be able to reliably reach any or all of the discharge standards shown in that table?

c. For those systems identified in (1a), if any of the system tests detected "no living organisms" in any or all of their replicates, is it reasonable to assume the systems are able to reliably meet or closely approach a "no living organism" standard or other standards identified in Table 1 of the White Paper, based on their engineering design and treatment processes?

Charge question 2: Potential performance of shipboard systems without reliable testing data

2. Based on engineering design and treatment processes used, and shipboard conditions/constraints, what types of ballast water treatment systems (which may include any or all the systems listed in Table 4 of the White Paper) can reasonably be expected to reliably achieve any of the standards shown in Table 1 of the White Paper, and if so, by what dates? Based on engineering design and treatment processes used, are there systems which conceptually would have difficulty meeting any or all of the discharge standards in Table 1 of the White Paper?

II. Assessment methods:

The Science Advisory Board subgroup members evaluated the available information (described below) for existing shipboard ballast water management systems (BWMSs) to answer theses charge questions. Ultimately, the goal of this process was to determine the availability of existing Ballast Water Management Systems (BWMSs) to meet the IMO D-2 discharge standard and standards more stringent than D-2.

Our evaluation proceeded as follows: data packages, reports, publications, certification documents, and other available information on the performance of BWMSs were compiled by the EPA through several means: solicitation of various Administrations that have granted Type Approval certifications, direct communication with developers and manufacturers of BWMSs, and searches for publically available sources (journal or conference publications and third-party reports provided through the internet). The SAB only considered information collected by the EPA. To maintain transparency and impartiality, group members then independently examined each data package. The amount of material in data packages varied, as some contained only a Type Approval certificate, while others included land-based and shipboard testing methods and data, documentation of G9 approval, a type approval certificate, and press releases describing the sale of systems for use on commercial vessels.

A. Assessing reliability of existing data.

A BWMS was scored as having 'reliable' or 'unreliable' data. At a minimum, the data package had to include methods and results from land-based or shipboard testing to earn a 'reliable' rating. A BWMS holding a certificate of type approval without supporting testing data was scored as having 'unreliable' data, as it was impossible to determine the validity of the testing procedures and, therefore, the data. If a BWMS's data package included one or more test reports, the data package was examined according to the following criteria:

- In general, is the operational type of system (e.g., deoxygenation + cavitation) appropriate for shipboard use (e.g., can it meet required flow capacities, size, power requirements, etc.)?
- Does the literature support the fundamental use of this approach (e.g., is it well known that using this approach in aquatic environments will safely and effectively remove, kill, or inactivate aquatic organisms)?
- Was laboratory testing conducted with 'reasonable and appropriate methods' (i.e., methods commonly used in aquatic studies or alternative methods that appear rigorous and equivalent to a standard, common approach)?
- Was land-based testing conducted with reasonable and appropriate methods; was sample size appropriately determined with statistical considerations in mind; was sample collection and handling appropriate and documented; did analytical facilities appear adequate; were IMO or ETV (v. 4.2) challenge conditions met; if necessary, were toxicological studies conducted; was a QA/QC policy followed? Did land-based testing produce credible results?
- Was shipboard testing conducted with the same considerations as land-based testing (as above)? Did shipboard testing produce credible results?
- If an active substance is included, does the BWMS have credible toxicity and chemistry data and G9 Basic approval or G9 Final Approval (which requires Basic approval)?
- Does it have Type Approval certification?
- Is it in operational use (i.e., not used only during shipboard Type Approval testing) on one or more active vessels? A BWMS without systems onboard vessels was not automatically categorized as having 'unreliable' data, but this information was useful.

Summing the answers from these questions, a BWMS was scored as having reliable or unreliable data.

B. Assessing ability of BWMS to meet discharge standards.
For BWMSs with reliable data, the system's ability to meet four discharge standards—IMO D-2/USCG Phase I (P-I) and 10x, 100x, 1000x more stringent than IMO D-2/USCG P-I—was determined. The following scores were assigned:

(A) Is demonstrated to meet the standard in accordance with the approach suggested in the IMO G8 guidelines (and G9 guidelines, if the BWMS employs an active substance)

(B) Is likely to meet the standard with reasonable scientific certainty[1]
(C) May have the potential to meet this standard
(D) Unlikely to or not possible to meet this standard

All of the BWMSs with reliable data were tested following the G8 guidelines, which suggest taking replicate samples with volumes of at least 1 m^3 for the size class of organisms ≥ 50 µm in minimum dimension (nominally zooplankton). Since the adoption of the G8 guidelines, however, it has been demonstrated that a time-integrated sampling approach with larger sample volumes will increase statistical confidence regarding whether zooplankton in sparse populations meet or exceed the D-2/P-I standard (Lemieux et al., in review; Miller et al., submitted; Lee et al., 2010). As such, some BWMSs were given a score of A/B: if the data showed they met the D-2/P-I standard by following the G8 guidance, they earned an 'A' (e.g., the BWMS was *demonstrated* to meet the standard using the G8 sampling approach). Those systems also received a 'B' if the number of living organisms was consistently low and it seemed very *likely* the BWMS would still meet the standard if larger, integrated sample were used.

Regarding the discharge standard 10x more stringent than the D-2/P-I, if the number of living organisms in all size classes was consistently low following testing (below the detection limit, often reported as zero, or not more than twice the standard), the BWMS was given a 'C'. The BWMS had *the potential* to meet the standard.

For the most stringent standards, 100x and 1000x more stringent than D-2/P-I, if any living organisms in any size class were found following treatment, a BWMS earned a 'D'. It seemed *extremely unlikely (or perhaps impossible)* the BWMS could meet a stricter standard, again because the detection limit of the test methods used provided resolution to D-2/P-I, at best. For example, if one zooplankter was found in testing using volumes of 1 m^3, the BWMS would be required to reduce the number of viable zooplankters to less than one in 100 m^3 or 1000 m^3 to meet the 100x and 1000x standards, respectively.

Next, group members collectively discussed their scores, reached consensus, and created Table 1. Rather than present the scores from individual, commercial BWMS units or models, the working group chose to categorize technologies by operation type (e.g., filtration + UV). The operation types were chosen from recently published, third-party data reports (Albert et al., 2010; Dobroski et al., 2010; Lloyd's List, 2010) to encompass all currently available operation types and to use standardized terminology. Thus, while the data packages from individual BWMSs were initially examined and scored, the results were collapsed to represent a top-order status of the field. For a given operation type, if reliable data were available for more than one commercial BWMS, the scores given to the operation type were the highest scores of any of the

[1]Reasonable scientific certainty is defined as: (a) rational basis built upon empirical scientific data that allows for drawing conclusions from data and (b) general acceptance by the relevant scientific community of the available data and methods, and the specific conclusions drawn from the data.

individual BWMS. In this manner, Table 1 represents the greatest potential of the operation types to meet various discharge standards.

III. Assessment results

Results of this assessment are presented in Table 3.1 and interpretations of the findings are provided below.

Table 3.1: Performance of Ballast Water Management Systems

Type or Category of BWMS	# BWMSs	# Type Approval Cert	# Available/Reliable Data	D-2/P-I	10x	100x	1000x
Deoxygenation	2	0	0				
Deoxygenation+cavitation	1	1	1	A/B	C	D	D
Deoxygenation+bioactive agent	1	0	0				
Electrochlorination	2	1	0				
Electric pulse	1	0	0				
Filtration	1	0	0				
Filtration+chlorine	2	0	0				
Filtration+chlorine dioxide	1	0	1	A/B	C	D	D
Filtration+coagulation	1	1	0				
Filtration+UV	10	3	3	A/B	C	D	D
Filtration+UV+TiO2	1	1	1	A/B	C	D	D
Filtration+ultrasound	1	0	0				
Filtration+ozone+ultrasound	1	0	0				
Filtration+UV+ozone	1	0	0				
Filtration+electrochlorination	5	0	2	A/B	C	D	D
Filtration+UV+ozone+ electrochlorination	1	0	0				
Filtration+electrochlorination+ advanced oxidation	1	0	0				
Filtration+cavitation+ electrochlorination	1	0	0				
Filtration+-electrochlorination+ ultrasound	1	0	0				
Filtration+cavitation+ozone+ electrochlorination	1	0	0				
Filtration+plasma+UV	1	0	0				

Filtration+cavitation+nitrogen+ electrochlorination	1	1	0				
Filtration+hydrocyclone+ electrochlorination	1	0	0				
Heat	1	0	0				
Hydrocyclone+filtration+ peracetic acid **	1	1	1				
Hydrocyclone+ electrochlorination	2	0	0				
Hydrodynamic shear+cavitation+ ozone	1	0	0				
Hydrocyclone+filtration+UV	1	0	0				
Menadione	1	0	0				
Mexel	1	0	0				
Ozone	1	1	0				
Ozone+cavitation	1	0	0				
Shear+cavitation+ozone	1	0	0				
Shear+cavitation+peracetic acid	1	0	0				

Based on one or more reliable data sets, the type of BWMS:
(A) is demonstrated to meet this standard in accordance with G8/G9
(B) is likely to meet this standard with reasonable confidence
(C) has the potential to meet this standard
(D) unlikely or will not to meet this standard
**Not scored because the one manufacturer has withdrawn this BWMS from market

IV. Response to charge question 1.

This analysis formed the basis of our responses to charge **Question 1a, 1 b, and 1 c**; each of these subquestions addresses different aspects of treatment capabilities for shipboard systems. These questions and our responses are summarized below:

Question 1 a: For the shipboard systems with available test data, which types or categories have been evaluated with sufficient rigor to permit a credible assessment of performance capabilities in terms of effluent concentrations achieved (living organisms/unit of ballast water discharged or other metric)?

Conclusion 1a: Five types or categories of ballast water management systems have been evaluated with sufficient rigor to permit a credible assessment of performance capabilities: Deoxygenation + cavitation, Filtration + chlorine dioxide, Filtration + UV, Filtration+UV+TiO2, and Filtration + electrochlorination.

Question1b: For those types or categories of systems identified in 1a, what are the discharge standards that the available data credibly demonstrate can be reliably achieved? Furthermore, do data indicate that certain systems (as tested) will not be able to reliably reach any or all of the discharge standards?

Conclusion 1b: The same five types or categories of ballast water management systems listed above have been demonstrated to meet the IMO D-2 and USCG Phase I discharge standards. With the limited data available, it is not possible to identify type or categories that will not be able to reliably reach any or all of the discharge standards.

Question 1c: For those systems identified above, if any of the system tests detected “no living organisms” in any or all of their replicates, is it reasonable to assume the systems are able to reliably meet or closely approach a “no living organism” standard or other standards identified in Table 1 of the White Paper, based on their engineering design and treatment processes?

To address this question, the Science Advisory Board agreed to define *reasonable scientific certainty* as: (a) rational basis built upon empirical scientific data that allows for drawing conclusions from data and (b) general acceptance by the relevant scientific community of the available data and methods, and the specific conclusions drawn from the data. The phrase *no living organisms* was also considered in two distinct ways: literally as the sterilization of ballast water and from a rational scientific perspective, as below method detection limits.

Based on the test data provided for several BWMSs, it is clear numbers of live organisms in discharged ballast water are reduced dramatically relative to intake water. The performance of the five BWMS types is duly impressive since the organism disinfection or removal efficiency is often reduced by four orders of magnitude, which exceeds that typically required for the performance of drinking water treatments. However, levels of organism removal do not achieve sterilization or the complete removal of all living organisms. The identification of just one live organism would indicate non-sterile conditions, and all systems evaluated had at least one living organism in at least one treatment sample (and often more). Unfortunately, in some cases, this low number of live organisms is not an unreasonable artifact that might result from contamination from scientific sampling gear (nets, buckets, etc.) or human counting error.

Alternatively, it is possible to establish specific detection limits (e.g., 100, 10, 1.0, 0.1, live organismsm^{-3} or ml^{-1}) for the methods used to collect the current performance data available and conclude that if numbers of live organisms are below those detection limits, they are statistically indistinguishable from zero or *no living organisms*. Efforts have been made to calculate the probabilities of meeting such a detection limit, using some assumptions, such as whether the organisms are randomly dispersed in space or spatially aggregated (see Lee et al. 2010 for details and examples). Not surprisingly, increased statistical power comes not only from increased sample size, but also from the difference between the set regulatory mean and the measured mean from a sample—the degree of compliance (or noncompliance).

Statistical power to assess samples against detection limits for testing and compliance monitoring also depends upon the sampling approach. When concentrations are close to the discharge standard, a single sample may require too large a volume of water to be logistically feasible. In that case, complete, continuous, time-integrated sampling (with the entire volume analyzed) and combining samples across multiple trials can improve resolution while maintaining statistical validity. As an example, conducting three trials of time integrated sampling of 7 m^3 (and analyzing the entire concentrated sample from the 21 m^3) from a ship's BW discharge can theoretically result in 80% or higher probability of detecting noncompliant discharge concentrations of 12 vs. 10 live organisms m^{-3} (Miller et al. 2010). Thus, pooling volumes from separate trials will allow lower concentrations to be differentiated from the discharge standard, although the practicability and economic costs of doing so have not been evaluated. Moreover, the practical limits of increased statistical sample sizes may already tax the capabilities of well-engineered ballast water test facilities.

In all statements (of meeting a regulatory standard) that are based upon statistical sampling, there is always a stated non-zero error probability (e.g., 0.1%, 1%, 5%) associated with a particular statistical conclusion. Thus, one can never claim to be 100% certain that, for example, the concentrations of live organisms $\geq$ 50 μm is below (say)10m^{-3}. More appropriate to statements about meeting a regulatory standard is the notion of *reasonable scientific certainty*. Based on available data, we can conclude with *reasonable scientific certainty* that several BWMSs can reliably perform to the IMO D-2 and USCG proposed Phase 1 discharge standard. However, current BWMSs are unlikely to ever meet 100x D-2 or 1000x D-2, and complete sterilization is simply not possible. Furthermore, our current sampling and analytical methods do not, and may never, allow for the resolution to state with reasonable scientific and statistical certainty that ballast water discharge meets any of these stricter standards.

To summarize **Conclusion 1c: It is not reasonable to assume that systems are able to reliably meet or closely approach a "no living organism" standard. Available data demonstrates that current ballast water management systems do not achieve sterilization or the complete removal of all living organisms.**

V. Response to charge question 2 related to prospective assessments of BWMS performance based on design and treatment processes.

Question 2: Based on engineering design and treatment processes used, and shipboard conditions/constraints, what types of ballast water treatment systems can reasonably be expected to reliably achieve any of the standards, and by what dates? Based on engineering design and treatment processes used, are there types or categories of systems, which conceptually would have difficulty meeting any or all of the discharge standards?

A diversity of system types are being used to manage ballast water (Table 1). The data indicate that several types of systems are proving reliable and effective, and Table 1 lists five types that have been demonstrated to meet the IMO D-2 standard. The five BWMS also appear to be mature technologies, with multiple active vessel installations, and are commercially available. Interestingly, four of the five systems include a filtration step, although the inclusion of filtration does not necessarily ensure that the BWMS will meet discharge standards.

Given the data available, it is also possible to assume that these same five systems have the potential to meet a 10X D-2/P-1 standard in the near future. As noted above, we make this prediction based upon available data that show viable organisms sampled as low (usually, below detection limits, see below). However, given the data available, it is highly unlikely that any of the systems listed in Table 1 could provide organism removal to the level of 100x or 1000x the standard because all systems showed at least one observation of a living organism within the sample volumes as specified in IMO D-2 guidelines, thus exceeding the hypothetically more stringent standards. No system reported zero living organism in all samples analyzed following treatment. We believe that ultimately different technologies, or treatment approaches, and sampling strategies will need to be considered to achieve these higher levels of removal (see Section 4, III. C. New approaches). At this point in time, it is not possible to comment on the likelihood that the other system types listed will or will not be able to meet either the D-2/P-1 or more stringent standards. All the BWMS types listed in Table 1 have likely shown some potential for reducing the number of ballast water organisms, but the data available for examination were deemed either to be absent or unreliable. As such, predictions of eventual performance of these BWMS are difficult to make.

VI. Environmental and Vessel Applications: Additional Constraints and Considerations that influence BWMS performance

Ballast water management systems are still evolving with an ever-growing number of manufacturers developing systems. Although several BWMSs have received Type Approval Certification, and appear to safely (they have received final G9 approval) and effectively meet D-2/P-I discharge standards (Table 1), there are several factors to consider beyond mechanical concerns and biological efficacy. Table 2 identifies broad environmental considerations and vessel operational concerns that affect the ability BWMS to work properly over a range of operational conditions. BWMS types identified in Table 1 as meeting at least the D-2/P-I discharge standard and treatment components being considered (e.g., filtration) are scored in their ability to operate under the various considerations. Note the table represents higher-order considerations; other issues relevant to a BWMS' performance are described below the table in the examples of specific vessel types.

Six priority considerations, listed as Environmental Application or Vessel Application, were identified for Table 2: Salinity (the ability to treat fresh, brackish and marine water), Temperature (the ability to work effectively in a variety of temperatures from warm equatorial to cold polar water), Ballasting Rate (the ability to treat water moving at a variety of flow rates from < 200 m^3hr^{-1} to > 4,000 m^3hr^{-1}), Ballast Volumes (the ability to treat total volumes of ballast water from < 1,000 m^3 to > 50,000 m^3), Hazardous Area Compatibility (e.g., intrinsically safe construction), and Corrosion (the potential of treatment to increase or decrease corrosion rates). Each BWMS and treatment was given a letter designation for each application (based on the data packages reviewed to generate the data in Table 1) as follows: A = Application proven in practice or in theory, B = Application not proven, but likely, C = Application not proven, but possible, D = Application unlikely. Additional explanation is also provided in the table as needed.

Table 3.2. Operational Considerations for Ballast Water Management systems' ability to work properly under a range of conditions

	Operational Considerations					
	Environmental Application		Vessel Application			
Category of BWMS	Range of Salinities	Range of Temperatures	Range of Ballasting Rates	Range of Ballast Volumes	Hazardous Area Compatibility	Corrosion
Deoxygenation+cavitation	A	A	A	A	B	A – demonstrated to reduce corrosion rate
Filtration+chlorine dioxide	B	B	B	B	B	C – strong oxidant may increase corrosion rate
Filtration+UV	B	B	B	B	B	B
Filtration+UV+TiO2	B	B	B	B	B	B
Filtration+electrochlorination	A – addition of brine required in freshwater	A – neutralization required in cold water	B	A	B	C – strong oxidant may increase corrosion rate
Treatment Components						
Electrochlorination	A – addition of brine required in freshwater	A –neutralization required in cold water	B	B	B	C – strong oxidant may increase corrosion rate
Filtration	A	B	C	C	B	B
Heat	B	C	C	C	C	B
Hydrocyclone	B	B	C	C	C	B
Ozone	B – addition of brine required in freshwater	B – neutralization required in cold water	B	B	C	C – strong oxidant may increase corrosion rate
Ultrasound	B	B	C	C	C	B
Peracetic acid	B	D – residual toxicity in cold water	B	B	B	C – strong oxidant may increase corrosion rate
Shear/cavitation	B	B	C	C	C	B

(A) proven in practice, (B) not proven, but likely, (C) not proven, but possible, (D) application unlikely

In addition to specific environmental and vessel applications, basic vessel type and operations can dictate BWMS applicability. While there are a multitude of vessel designs and operation scenarios, there are a few important examples of specific constraints that can greatly limit treatment options. Perhaps the most dramatic limitations are found with the Great Lakes bulk carrier fleet that operates vessels solely within the Great Lakes with large volumes of fresh, and often cold, ballast water ('Lakers'). The vessels in this fleet have ballast volumes up to 50,000 m^3, high pumping rates (up to 5,000 m^3hour^{-1}), uncoated ballast tanks, and some vessels have separate sea chests and pumps for each ballast tank. A further confounding issue is that voyages taken by Lakers average four to five days, with many less than two days. Given these characteristics, a number of limitations are imposed: electrochlorination and ozonation will only work in freshwater with the addition of brine (in particular Cl and Br, respectively); oxidizing chemicals may increase the corrosion rate of uncoated tanks; deoxygenation and chemical treatments that require holding times to effectively treat water (or for the breakdown of active substances) may not be completely effective on short voyages; and the space and power needed for the required numbers of filtration + UV treatments may simply not be available.

Another example of vessel-specific constraints is the sheer size of some vessels and the cargo they carry. Very Large Crude Carriers (VLCC) and Ultra Large Crude Carriers (ULCC) can carry up to 100,000 m^3 of ballast and can fill or discharge ballast water at over 5,000 m^3hour^{-1}. While various BWMS may be modular (with perhaps the ability to add several units in a manifold design or in sequence), systems that include a mechanical separations stage (e.g., filtration, hydrocyclone) or exposure to UV or sonication may have difficulty addressing these large volumes and flow rates. Furthermore, given the hazardous nature of the cargo carried on these ships (and other similar vessels, such as Liquefied Natural Gas carriers), restrictions on the placement of a specific BWMS may apply and system components will likely have to satisfy classification society requirements for explosion proof and intrinsically safe construction, which might be more difficult for some treatment types than others.

A final example is the treatment of ballast water on the tens of thousands of unmanned barges in the U.S. that would fall under the ballast water discharge regulations. Inland waterways and coastal barges are not self-propelled, but rather are moved by towing or pushing with tugboats. Because these vessels have been designed to transport bulk cargo, or as working platforms, they commonly use ballast tanks or fill cargo spaces with water for trim and stability, or to prevent excessive motions in heavy seas. However, the application of BWMSs on these vessels presents significant logistical challenges because they typically do not have their own source of power or ballast pumps and are unmanned.

VIII. Summary of charge questions and conclusions regarding BWMS performance

Question 1 a: For the shipboard systems with available test data, which types or categories have been evaluated with sufficient rigor to permit a credible assessment of performance capabilities in terms of effluent concentrations achieved (living organisms/unit of ballast water discharged or other metric)?

Conclusion 1a: Five types or categories of ballast water management systems have been evaluated with sufficient rigor to permit a credible assessment of performance capabilities: Deoxygenation + cavitation, Filtration + chlorine dioxide, Filtration + UV, Filtration+UV+TiO2, and Filtration + electrochlorination.

Question1b: For those types or categories of systems identified in 1a, what are the discharge standards that the available data credibly demonstrate can be reliably achieved? Furthermore, do data indicate that certain systems (as tested) will not be able to reliably reach any or all of the discharge standards?

Conclusion 1b: The same five types or categories of ballast water management systems listed above have been demonstrated to meet the IMO D-2 and USCG Phase I discharge standards. With the limited data available, it is not possible to identify type or categories that will not be able to reliably reach any or all of the discharge standards.

Question 1c: For those systems identified above, if any of the system tests detected "no living organisms" in any or all of their replicates, is it reasonable to assume the systems are able to reliably meet or closely approach a "no living organism" standard or other standards identified in Table 1 of the White Paper, based on their engineering design and treatment processes?

Question 2: Based on engineering design and treatment processes used, and shipboard conditions/constraints, what types of ballast water treatment systems can reasonably be expected to reliably achieve any of the standards, and by what dates? Based on engineering design and treatment processes used, are there types or categories of systems, which conceptually would have difficulty meeting any or all of the discharge standards?

Conclusion 2: Five types or categories of ballast water management systems can currently meet IMO D-2 and USCG Phase I discharge standards(Deoxygenation + cavitation, Filtration + chlorine dioxide, Filtration + UV, Filtration+UV+TiO2, and Filtration + electrochlorination) and it is possible that the same five types could meet 10x D-2/P-I sometime in the near future. With the limited data available, it is not possible to identify type or categories that may have difficulty meeting any or all of the discharge standards.

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Subgroup 2

Section 4. Draft Response to charge question 3: System development

I. Introduction:

This section addresses issues raised in charge question 3 regarding further development of ballast water treatment systems, especially technological options for potential improvements and impediments to improvement.

Charge Question 3a. *For those systems identified in questions la and 2, are there reasonable changes or additions to their treatment processes which can be made to the systems to improve performance?*

Response

In 2004 the International Maritime Organization adopted the Ballast Water Convention that provided a discharge standard commonly referred to as “D-2.” This published standard has provided a stable target to support the research, development, testing, and evaluation of ballast water treatment technologies. Using this standard, the development cycle has balanced the following:

- Integrating technology within marine vessel arrangements, weight and stability constraints, electrical distribution and piping systems, and automation control systems.
- Integrating technology operations within marine vessel operational demands such as ballasting rates and volumes, logistics requirements such as reliable chemical supply chains and service/support centers, safe operations such as hazardous rated equipment and chemical handling procedures, operational training.
- Tuning the technology to an acceptable level of disinfection byproducts, residual toxicity, within the limits of practical integration and compliance with the efficacy standard.
- Packaging the technology for a commercially competitive market considering life cycle costs, equipment reliability and maintainability, and mariner familiarity or acceptability of equipment.

Existing technology has been optimized to meet the D-2 standard. There are reasonable changes, requiring additional expense and complexity, that could provide incremental improvements in efficacy. The following comments on possibilities to improve performance do not consider possible ship-board constraints (which are addressed in response to charge question 3.b. Part A):

- Deoxygenation + cavitation – Anoxia has already been established in these systems and cannot be improved upon. However, increasing the degree of cavitation may increase performance by greater mixing and thus exposure of organisms to anoxia.
- Filtration + chlorine dioxide – Filtration could be optimized and contact time for chlorine dioxide exposure could be increased.
- Filtration + UV - Filtration could be optimized and contact time/dosage with UV could be increased.
- Filtration + UV + TiO_2 – Filtration could be optimized, contact time/dosage with UV could be increased as could dosage of TiO_2 with the caveat that the dosage of the latter not become so great as to itself pose potential environmental harm on discharge.

Combinations of the systems above would result in improved performance, and we recommend that trials be conducted to determine optimum combinations. “Tweaking” existing technologies will only result in incremental improvements toward meeting published standards. New technologies will be needed for 100X and 1000X IMO regulations, and shipboard systems should not be the only possibilities considered (see response to charge question 4).

Meeting Higher Standards

As more stringent discharge standards are considered, technology development can consider either incremental improvements to existing applications, or new approaches utilizing technology that has not typically been applied on marine vessels. As suggested earlier in this response to the charge question, incremental improvements offer the fastest path to meeting higher discharge standards by "turning up the dial." New approaches, possibly from the wastewater treatment industry, may also reach those standards, but will take more time to develop and trial to determine practicality and cost impacts.

These higher standards also increase the importance of process control. For example, with respect to D-2's zooplankton fraction ($\geq$ 50 µm minimum dimension), trials must demonstrate a 4-log reduction from specific "challenge water" conditions to fewer than 10 organisms per cubic meter. For a 5,000 m^3 discharge, this standard limits the discharge to 50,000 organisms. As stringent as this standard is, there is some inherent allowance for:

- Organisms released during treatment system start-up or shut-down.
- Intermittent periods that exceed challenge conditions due to "patchiness" of organisms, as could be caused by ballast uptake in an algal bloom, or while discharging the bottom of a ballast tank that has a high load of sediment and settled organisms.
- Lag time as control systems adjust to changing ballast pumping flow rates, increases in uptake water turbidity, or other changes due to the natural environment or marine vessel operational demands.

More stringent discharge standards, ones requiring a 5- or 6-log reduction, reduce the zooplankton allowance for this example 5,000 m^3 discharge to 5,000 or 500 organisms. Meeting this standard may require fundamental changes to ballasting routines that include separate dedicated uptake and discharge piping, and recirculation loops to verify efficacy prior to ballast water discharge.

In the following two sections, we separately consider incremental improvements and new approaches to ballast-water treatment. The former elaborate on the "bullet points" listed in the "Answer" section above. The latter are offered with the intent of considering long-term improvements in performance of ballast-water treatments.

Incremental Improvements

Incremental improvements to existing technologies are based on the concept of "turning up the dial." The development cycle for these incremental improvements unfortunately is not simple. This approach needs to consider two aspects: it may not be possible or practical to further improve the baseline technology, and the improvement in efficacy could fundamentally alter other aspects of the technology development cycle, i.e., life cycle costs, integration, or residual toxicity. In summary, these incremental improvements are not always simple or straightforward. The following sections consider the baseline technologies identified in Table 1 (See Group 1 Table). For each, the improvements for increased efficacy are identified, and then challenges to the development cycle are discussed.

Filtration + UV

Ultraviolet radiation (UV) is widely deployed in industry and used on marine vessels to disinfect potable, technical, and waste water streams. In the context of ballast-water treatment, several technologies have successfully demonstrated application of UV.

The efficacy of UV is dependent on matching the wavelength to the targeted organism and pathogens, intensity of the radiation, accounting for transmissivity of the water, and the resulting exposure time. Effective application of UV is further dependent on the physical configuration and fluid dynamics of the UV chamber to ensure adequate intensity and exposure time to the entire flow stream. Of the three classes of UV radiation, UVA penetrates water the best but is less lethal. UVC penetrates water the least but is most lethal and UVB in intermediate in penetration and lethality.

To meet the D-2 standard, technology suppliers have developed and trialed their systems to balance these multiple process components. In general, efforts to meet a higher standard will require larger UV chambers, more significant pre-treatment of the ballast water, and more complex controls. In short, it is possible to increase the efficacy of existing systems beyond the D-2 standard, but only with more space, radiation intensity, complexity, and expense.

It may be possible to deploy an “oversized” treatment system. For example, a ballast system that runs at 800 m^3 per hour could be paired with a treatment system rated for 1,000 m^3 per hour, thereby effectively increasing UV exposure by 20%. Analysis would be needed to determine how much the system’s efficacy was increased, and to assure the fluid dynamics of the UV chamber were not adversely impacted.

Similar to use of an “oversized” treatment system, the intensity of the UV lamps could be increased to improve efficacy. Also, the length of time the ballast water was exposed to UV could be increased by increasing the size of the chamber relative to the ballasting rate. Such improvements would directly impact system cost, and size of the equipment.
It is possible to stage several UV chambers in series. The obvious impact of such an effort would be a substantial increase in cost, required space, and maintenance. This approach, however, offers to improve several aspects of a UV-based system:

- Use of multiple chambers decreases the chance that an organism can “slip” past treatment, assuming each chamber on its own is capable of reaching the required standard.
- Multiple chambers may allow a supplier to utilize different lamps emitting different wavelengths (UVA to UVC). Individual chambers may be “tuned” to a spectrum targeting certain kinds of organisms.
- Multiple chambers would allow increased exposure time of organisms to the UV.

Transmissivity (clarity) of ballast water and exposure to organisms can be increased by employing higher levels of filtration upstream of the UV chamber. Further, flocculants such as alum and other means could further clarify the ballast water prior to its entry into the UV chamber. These higher levels of filtration will require significant increases in expense and space. In addition, advanced filtration is likely to significantly increase system backpressures, resulting in a need for higher head ballast pumps and additional electrical power.

Deoxygenation

Two Type Approved ballast water treatment systems utilize deoxygenation as part of their treatment process. However, both of these systems also rely on multiple additional processes to meet the D-2 standard and thus are complex processes.

The Venturi Oxygen Stripping (VOS) System lowers the oxygen by pumping low-oxygen exhaust gas from a purpose-built burner into the ballast-water stream through a venturi device. The efficacy of this system is reliant on the rapid application of this gas stream, the creation of carbonic acid resulting from carbon dioxide in the gas stream, which lowers pH making the low oxygen environment more lethal, and the mechanical effect of the venturi on the passing organisms.

The VOS system lowers the oxygen level to about 2% by volume utilizing a variation of traditional tank-ship combustion-based inert-gas generators. The traditional units typically produce a 5% oxygen level. Further optimizing a combustion-based unit to provide oxygen levels <2% may not be practical given the combustion process. As a reference point, 3.0% oxygen level is considered the upper boundary for environmental hypoxia and the point of mortality for sensitive species. Very few higher organisms can survive 2% oxygen for longer than 24 hours.

The Ocean Saver Ballast Water Treatment System lowers oxygen levels through the use of a nitrogen generator. These generators utilize a membrane to filter ambient air, resulting in high quality nitrogen gas. The Ocean Saver process also includes filtration, cavitation, and an electrodialytic disinfection process.

Nitrogen generators are widely deployed in industry and in some marine applications. They are generally considered expensive and high consumers of electrical power in shipboard applications. It is possible to produce very high quality nitrogen gas, approaching 99.9% pure, but at significant space, capital cost, and electrical power demands.

Due to the complexity of treatment systems that utilize deoxygenation, the impact of incremental improvements on efficacy is not obvious. In fact, some changes might decrease the system's efficacy or worse, resulting in unanticipated adverse conditions, e.g., higher populations of sulfate-reducing bacteria and a subsequent increase in steel corrosion rates. With respect to deoxygenation, therefore, it is not clear whether an effort to "turn up the dial" will result in meeting a higher standard. Relative to lethality for higher organisms, there will be little to no difference between a 2% oxygen level and 1% for the same contact period. Extending holding time would be more efficient than additional efforts to reduce oxygen below 2%.

Oxidant-Based Systems

Oxidant-based systems introduce a reducing agent, such as chlorine, into the ballast-water stream. For the purposes of mechanical considerations, this process includes adding chemical in bulk, on-site manufacture of sodium hypochlorite or similar chemicals, and on-site production of

ozone gas. Oxidant-based systems generally target a level of residual oxidant in the treated ballast water.
As the organic-matter content of ambient water taken up as ballast water varies, so will the consumption, or oxidant demand, of the oxidant introduced by the treatment system. After an initial instantaneous demand is consumed, any remaining oxidant will be pumped with the ballast water into the vessel's ballast tanks. There the water is held for a prescribed length of time at the targeted residual oxidant concentration. The residual will decay over time as a function of many factors, including its initial concentration, salinity, temperature, motions of the vessel, and configuration of the ballast tank and venting system. Depending on predicted or measured oxidant levels in the ballast water, a neutralizing agent may be applied before or during its discharge to the environment.

The efficacy of oxidant-based systems is a function of concentration of the residual oxidants and the hold time. Improvements to efficacy include: increasing initial oxidant concentrations; maintaining a higher oxidant concentration during the hold period; and increasing the hold period or contact time. These several options are considered in the following subsections. Combining the oxidant with other processes is considered a combination approach, and is considered in a later section.

>>Increasing initial oxidant concentrations
Determining the initial oxidant concentration to reach the required efficacy is part of the "art" of a ballast-water treatment system. IMO Basic and Final Approval applications provide values for various treatments: 2.5 mg/L total residual oxidant (TRO) for Ocean Saver; 3.16 mg/l chlorite ion for EcoChlor; 15 mg/L TRO as Cl_2 for BalPure; 1.0 parts per million of free active chlorine for Sedinox; and 2.2 and 4.2 mg/l of ozone and TRO, respectively, for NK-03 Blue Ballast. Several oxidant-based systems also use some form of filtration, which serves to remove larger organisms and some particulate organic matter and thereby reduces oxidant demand. Regardless of filtration's effectiveness, however, residual oxidants and other disinfection byproducts remain the active substances. As such, filtration may reduce the amount of chemical required, but is not expected to improve the efficacy of the oxidant. Tertiary impacts, such as damage to organisms' membranes incurred during the filtration process, and the membranes' subsequent interaction with oxidant-based systems, are difficult to analyze and therefore not obvious as an incremental improvement of existing technologies.

It is possible with existing systems to "turn up the dial" and increase the amount of oxidant introduced to the ballast water, which should result in increased efficacy. Increasing oxidant concentrations simply requires that a higher capacity ballast-water treatment system be installed. For example, concentrations could be increased 50% by installing a system rated for 1200 m^3 per hour on a vessel that pumps ballast water at 800 m^3 per hour. Such an installation will demand larger space and weight allowances, more power, and higher capital and operating costs. In general, integration of higher capacity systems should be possible for new vessel designs, and more challenging for existing vessels on a retrofit basis.

Higher oxidant levels in the ballast water can have a significant and negative impact on piping-system components and tank-coating systems. Valve packing, flange gaskets, and pump seals are made of a variety of materials, some of which are not compatible with oxidants at low concentrations, and less so at increasingly higher ones. Impacts on tank coatings are not yet well understood. TRO levels up to 10 mg/l may be compatible with typical, intact, ballast-tank marine coatings. Coatings are frequently not intact, however, as they wear over time or are not applied at all in freshwater shipping applications. Corrosion of exposed carbon-steel structure can lead to structural failures and repairs that are expensive and complex. Increased oxidant levels, therefore, will likely increase the rates of coating failures and corrosion of exposed carbon-steel structure.

Higher oxidant levels also increase safe-handling concerns on board vessels through resultant hydrogen generation, additional bulk chemicals to handle and store, and increased times to make confined tank spaces safe for entry for inspection and repair work. These concerns can be handled through procedures and plans, but at the expense of increased time and effort.
As higher levels of oxidants are introduced into ballast water, complex chemical reactions take place, resulting in potentially harmful disinfection byproducts. These byproducts are impacted by the interaction between the oxidant level and characteristics of the uptake water such as its organic load, alkalinity, salinity, and chemical contaminants. Further testing and analysis will be needed to determine whether these byproducts need to be or can be effectively neutralized, such that the ballast water will have an acceptable toxicity level prior to its discharge.

>>Maintaining or increasing oxidant concentrations
Most oxidant-based systems rely on residual-oxidant levels adequate to meet the D-2 standards and maintaining that concentration for the duration of the holding period. The hold time of ballast water can vary significantly, however, and schedule, weather, equipment failure, and cargo-handling changes frequently result in longer- or shorter-than-expected hold times. As hold times increase, the residual-oxidant concentrations decay, which also reduce detoxification costs. Most efficacy testing has occurred during a regimented holding period, typically for two to five days. In reality, ballast-water hold times routinely range from one day to several weeks. In fact, some ballast tanks can remain full, or partially full, for many months or even years.

There has been little development or testing of systems that monitor and maintain a specific oxidant level in ballast-water tanks. Indeed, automated monitoring of oxidant levels in ballast-water tanks is not currently practiced. Continuous or periodic monitoring would require either a network of sensors installed in the tanks or a means of drawing a liquid sample on a periodic basis to a remote monitoring device. Either approach requires significant cabling, possibly tubing and pumps, monitoring equipment, and data-recording devices.

Current practice to maintain an oxidant level, if done at all, is to “top up” a ballast tank, i.e., to partially discharge its contents, then refill with freshly treated water. The objective is to achieve the desired oxidant level by mixing the “new” water having a high concentration of oxidant with the water remaining in the tank. Such efforts are similar in mechanical function to ballast-water exchange, would likely be performed while the vessel is at sea, and carry with them the same significant safety concerns regarding vessel stability.

A more reliable and safer approach for topping up oxidant levels will require new systems that are not currently available. Such systems might include chemical dosing lines to deliver an external supply to each ballast tank, combined with circulation devices internal to each ballast tank.

>>Increasing the hold period

Increasing the hold time of the ballast water while maintaining a certain oxidant level would likely increase efficacy. However, it is ship operations that will dictate the duration of this hold time for most ballast water tanks. In particular, the largest mid-body, ballast-water tanks almost always have to be discharged while tank ships or bulk carriers are being loaded. As such, the treatment process must account for the expected hold period, but likely will not have the ability to alter it.

>>Summary

Existing oxidant-based systems have been developed to meet the D-2 standard, and several have gained international approvals. Their efficacy could be increased by increasing initial residual oxidant levels in ballast water during uptake. However, testing would need to be conducted to understand how much this efficacy would be increased by these higher doses. In addition, toxicity impacts from the disinfection byproducts of these higher doses must be studied before proceeding. Increasing residual oxidant levels will impact the vessel through greater demands for space, weight, power, and capital and operating expenses; in addition, they will increase piping-system compatibility issues, ballast-tank corrosion rates, and safe-handling concerns. It may be possible to increase efficacy by maintaining residual oxidant levels during holding time in the ballast-water tanks. Current systems, however, have only rudimentary methods for performing such operations. New methods will need to be developed and trialed to determine their practicality and effect.

Filtration and Cavitation

Ballast-water treatment systems have extensively utilized filtration as a primary step for other processes such as ultraviolet radiation or oxidants. Filtration serves multiple purposes that vary according to the treatment's disinfection processes: screening of larger organisms that may be resistant to disinfection; reduction of organic matter to reduce oxidant demand; and reduction of turbidity to increase transmittance of ultraviolet system.

Filtration also has a secondary effect of mechanically damaging some of the organisms as they pass through the device. This effect may inactivate or kill the organisms or weaken their cellular structure such that effective disinfection is more easily achieved. In this way, filtration is similar to cavitation devices designed to impart physical damage.

Traditional seawater filtration on vessels has been limited to protecting mechanical devices in the piping system. For example, seawater might be "screened" to a one-eighth inch opening (3.175

mm) to protect the narrow passages of a heat exchanger. Recently, however, several common and proprietary devices have been developed for filtering and imparting cavitation effects on ballast water as part of the treatment process: variations on back flushing of traditional screen filters; vibrating disc filters such as the Arkal Spin Klin units; multi hydro-cyclone used by Green Ship; and various cavitation devices. In general, the filter units target removal of particles above 40 or 50 µm and have significant waste streams that are returned to the ambient water. Typically, filtering takes place on ballast water uptake only.

The efficacy levels of these filtration devices are advertised in percentage removal. For example, Ballast Safe and Hydac claim filtration rates of approximately 90 percent removal of zooplankton. These removal levels, although essential to support the disinfection process, by themselves are far below the D-2 standard for the size class $\geq$ 50 µm.

It is not reasonable to expect incremental improvements in filtration devices to offer significant improvements in efficacy over the D-2 treatment standard. Such improvements will require the application of media filters, membrane filters, or other devices that have not yet been practically applied to ballast-water treatment. Cavitation devices similar to filters cannot meet the D-2 standard alone. It is not clear if improving these cavitation devices will have a significant impact on the efficacy of the combined processes.

Combination Technologies

Most ballast-water treatment systems, even those with a single primary component, are actually combination technologies. For example, the VOS System is primarily a deoxygenation system, but also has other effects at work: the venturi device mechanically damages some of the organisms as would a cavitation device, and the carbon dioxide forms carbonic acid, lowering the pH of the water. And the PureBallast system is advertised as a combination technology that includes filtration, ultraviolet radiation, and free radicals.

It is difficult to understand fully the interactions of combined ballast-water treatment technologies. For example, Resource Ballast Technology combines filtration, cavitation, ozone, and injects sodium hypochlorite. With four "primary" technologies at work, which one(s) should be the focus for "turning up the dial" to reach a higher efficacy standard? Further complicating matters is the high physical and chemical variability in the ballast water itself, and how it reacts with each technology and combination thereof.

The development of combination technology to date is a result of research and testing. It is important to note that once a technology has shown promise to meet the D-2 standard, its development has been stopped in order to allow the device to undergo certification efforts. As such, it is reasonable to assume that combination technologies can be incrementally improved in terms of efficiency of operation (less power, less cost, more reliability) and efficacy. Due to the complex interactions of these technologies, however, improving and optimizing their combinations can only be speculative until the concepts are trialed.

New Approaches – Overview and perspective on higher standards

Ballast-water discharge standards 1000 times more stringent than the D-2 standard are being considered by the US Coast Guard. As argued above, however, it is unlikely current management approaches and treatment technologies will meet these significantly more challenging standards.

In part, the inability to do so stems from design characteristics of present-day treatment technology, which is placed "on top" of existing ballast-piping systems. Thus, standard ballast pumps and piping systems are used, with treatment calling for addition of filters, passage through UV lamps or cavitation devices, and possibly chemical-injection ports. Ballast water is taken up, held, and discharged in essentially the same manner as in the past. Furthermore, compliance monitoring and enforcement programs are currently under development. As they are revised, they may likely reveal "gaps" in ships' ability to maintain ballast water in a "treated" status during long holding durations, and under circumstances for which treatment-system suppliers have not designed their systems.

To meet higher standards, and to account for the variety of circumstances a vessel's ballast water experiences, new approaches to management and new technologies will be required. The following subsections develop a vision of these new approaches and technologies by:

- Placing higher standards into perspective for vessels' ballast capacities.
- Identifying key technology and management considerations for meeting higher standards.
- Identifying key elements of an idealized shore-side plant for treating ballast water.
- Conceptualizing new management approaches and technologies for meeting higher standards on board a vessel.

Perspective on Higher Standards

Multiple ballast-water treatment systems have demonstrated successful compliance--under testing conditions-- to the IMO D-2 standard. The D-2 standard is a four-log reduction in the number of zooplankton-sized organisms, those $\geq$ 50 µm in minimum dimension, relative to the "challenge water" called for in US EPA's Environmental Technology Verification (ETV) protocol for testing ballast-water treatment systems. For a very large crude carrier (VLCC) tanker, this standard allows a treated water volume of 90,000 m^3 to contain a maximum of 900,000 zooplankton.

The US Coast Guard's proposed Phase 2 standard for zooplankton is a seven-log reduction from the ETV challenge-water conditions, equivalent to a 99.99999% reduction, referred to in reliability engineering as "seven-nines." [Equation 1] For the VLCC example, this standard limits the viable zooplankton discharge to a maximum of 900 individuals, fewer than half the number of zooplankton contained in a five-gallon bucket of challenge water. [Equations 2 and 3] Consider these values in the context of vessel onboard practice. VLCCs typically discharge ballast water at 5,000 cubic meters per hour. One second of discharge at this rate would total 1.39 cubic meters of ballast water. Assuming a 900 millimeter nominal ballast pipe, this 1.39 cubic meters of ballast water would be contained in a length of 2.2 meters of ballast water pipe. Assuming challenge water conditions, this one second of discharge or 2.2 meter length of pipe would contain 139,000 zooplankton. This one second discharge or short stub of pipe when compared to the allowable discharge for the entire VLCC ballast capacity would exceed: Phase 2 standard by 154 times; D-2/100 Standard by 15 times; and D-2/10 Standard by 1.5 times.

$$\boldsymbol{Phase\ 2\ Reduction}\ (percentage\ reduction\ organisms\ \geq 50\ microns) = 1 - (Maximum\ Allowed\ by\ Phase\ 2\ Rule\ \div Minimum\ Count\ in\ ETV\ Challenge\ Water)$$
[Equation 1]

$$\boldsymbol{Phase\ 2\ Reduction}\ = 1 - (1\ per\ 100\ cubic\ meters\ \div 100{,}000\ per\ cubic\ meter) = 1 - (0.010\ \div 100{,}000) = 99.99999\%$$ [Equation 1]

$$\boldsymbol{Phase\ 2\ Maximum\ Discharge}\ (number\ of\ organisms\ \geq 50\ microns) = Discharge\ Standard\ \times Ballast\ Discharge\ Volume$$ [Equation 2]

$$\boldsymbol{Phase\ 2\ Maximum\ Discharge\ for\ VLCC} = 1\ per\ 100\ cubic\ meter\ \times\ 90{,}000\ cubic\ meters = 900\ organisms\ \geq 50\ microns$$
[Equation 2]

$$\boldsymbol{Challenge\ Water\ (Raw\ Seawater) Minimum\ Concentration}\ (number\ of\ organisms\ \geq 50\ microns = Challenge\ Water\ Criteria\ \times\ Ballast\ Water\ Volume$$ [Equation 3]

$$\boldsymbol{Challenge\ Water\ Minimum\ Concentration\ for\ 20\ liter\ Bucket} = 100{,}000\ per\ cubic\ meter\ \times\ 20\ liters = 2{,}000\ organisms\ \geq 50\ microns$$ [Equation 3]

$$\boldsymbol{Phase\ 2\ Allowable\ Discharge\ VLCC} = 1\ per\ 100\ cubic\ meter\ \times\ 90{,}000\ cubic\ meters = 900\ organisms\ \geq 50\ microns$$
[Equation 2]

Similar challenges are also apparent for smaller-capacity vessels. Under Phase 2, the number of zooplankton allowed to be discharged by a small containership or a typical passenger ship would be fewer than 35 individuals, equivalent to the number in a volume of challenge water that would fill a bottle of beer (Table 4.1).

Table 4.1 – Zooplankton Counts for Water and Increasing Log Reductions from D-2 Standard. The US Coast Guard's proposed Phase 2 standard is represented by in the column labeled "D-2/1000".

	Volume	Rate	*Viable Organisms >50 um (Seawater per US ETV)*				
Volume Basis	***(m3)***	***(m3/hr)***	**Seawater**	**IMO D-2**	**D-2/10**	**D-2/100**	**D-2/1000**
Test Standards	1.00E+00	NA	1.00E+05	1.00E+01	1.00E+00	1.00E-01	1.00E-02
VLCC Tanker	9.00E+04	5.00E+03	9.00E+09	9.00E+05	9.00E+04	9.00E+03	9.00E+02
Great Lakes Bulk Carrier	4.40E+04	1.00E+04	4.40E+09	4.40E+05	4.40E+04	4.40E+03	4.40E+02
Handymax Bulk Carrier	1.80E+04	1.30E+03	1.80E+09	1.80E+05	1.80E+04	1.80E+03	1.80E+02
Panamax Container	1.70E+04	5.00E+02	1.70E+09	1.70E+05	1.70E+04	1.70E+03	1.70E+02
Feedermax Container	3.50E+03	4.00E+02	3.50E+08	3.50E+04	3.50E+03	3.50E+02	3.50E+01
Passenger Ship	3.00E+03	2.50E+02	3.00E+08	3.00E+04	3.00E+03	3.00E+02	3.00E+01
ETV Testing Tank	2.00E+02	2.00E+02	2.00E+07	2.00E+03	2.00E+02	2.00E+01	2.00E+00
VLCC Pipe (2.2 meters)	1.39E+00	5.00E+03	1.39E+05	1.39E+01	1.39E+00	1.39E-01	1.39E-02
Bucket (20 liters)	2.00E-02	NA	2.00E+03	2.00E-01	2.00E-02	2.00E-03	2.00E-04
Beer Glass (0.4 liters)	4.00E-04	NA	4.00E+01	4.00E-03	4.00E-04	4.00E-05	4.00E-06

Table 4.1 relates zooplankton treatment standards to maximum numbers of viable organisms for various volumes. The top row provides organism counts in one cubic meter for water, as per ETV challenge-water conditions, the D-2 standard, and finally for successive log reductions beyond D-2. Several vessels are listed showing typical ballast-water volumes and flow rates. For each volume, the number of organisms in water and the maximum number of organisms allowed for each of the discharge standards are tabulated.
Table 4.1 also indicates the number of zooplankton in ETV challenge-water volumes equivalent to a glass, a bucket, and that displaced by one second of untreated discharge from a VLCC. The highlights indicate when the glass, bucket, or discharge contains more viable organisms than the total volume of a treated vessel discharge.

The practical implication of these higher standards is that piping systems must be carefully designed to avoid the discharge of any untreated ballast water, however minimal the volume. This implication has the following requirements:

- Separate uptake and discharge ballast-water piping may be required. Current standard practice is to use a common piping system for both uptake and discharge.
- To allow for any brief interruptions in the treatment process during start-up or shut-down, treated ballast water may need to be re-circulated to confirm its treatment status before discharge.

<u>Key Technology and Management Considerations for Meeting Higher Standards</u>
In considering future management approaches and technologies, maximizing energy efficiency is increasingly important for vessels. This strategy is driven not only by rising fuel costs, but also by possible valuations on air emissions such as sulfur oxides, nitrogen oxides, particulate matter, and other contaminants. Further, a carbon-taxing scheme is under development for maritime

shipping at the IMO. To date, efforts to meet discharge standards have generally increased the energy required for ballast management. New approaches should attempt to reverse this trend. Recent management efforts have significantly reduced the actual volume of discharged ballast water, and in some cases eliminated discharges in all routine operations. Such direct approaches should continue to be developed, and regulatory, monitoring, and enforcement efforts should recognize the real reduction in environmental impact from these practices. As these are not technology-based approaches, however, they are not further reviewed here.

Finally, meeting higher standards will require consideration of: efficacy of filtration and disinfection technology; in-tank monitoring, treatment, and mixing; and controls to avoid contamination from sources such as adjacent tanks, piping systems, and debris or fluids falling into tank accesses. These three considerations are elaborated upon in the following subsections.

>>Efficacy of filtration and disinfection technology
Meeting higher standards will require large improvements in filtration and disinfection technology . Application considerations include:
Handling the heterogeneity or "patchiness" of water on uptake and treated water on discharge.

- For example, treated ballast water at the bottom of a tank may have a high sediment load. When stripping these tanks, sediment particles would reduce the efficacy of a UV system designed to operate on discharge.
- Providing a positive, or fail-safe, barrier to the release of untreated ballast water. With the proposed Phase 2 standard requiring "seven-nines," this implies 100% efficacy with only 3.15 seconds of interrupted service per year of operation. [Equation 4]

$Down\ Time = Duration - (Reliability\ \times Duration)$ [Equation 4]
$Down\ Time = (Duration\ (years) - \big(Reliability\ (percentage) \times Duration\ (years) =$
$(1\ year - 99.99999\% \times 1\ year \times (3.15E07 seconds year) = \ \ 3.15\ seconds$ [Equation 4]

>>In-tank monitoring, treatment, and mixing
Meeting higher standards will require careful monitoring of in-tank conditions. This becomes particularly important when: hold times are very long and organism may re-grow; hold times are very short and treatment processes may not have adequate time to take effect; sediment loads protect a layer of organisms from the disinfection process; "patchiness" in the uptake challenge water overwhelms the treatment process during ballast-water uptake. Application considerations include:

- Means to monitor tank conditions. This is particularly challenging because typical ballast-water tanks are very complex, and are known to have hydrodynamic "dead zones" not flushed out in a typical ballast cycle.
- Means to treat a full ballast-water tank. A full tank may require treatment, or re-treatment, for numerous reasons including: ineffectiveness of the uptake process; contamination from external sources; and exceedance of expected hold time duration.

- Means to mix a full ballast-water tank. An ideal mixing system would suspend sediment loads, preclude untreated pockets of ballast water, permit representative monitoring of the tank, and provide a means of evenly treating a tank's contents.

>>Controls to avoid contamination
Contamination is always of concern, especially so when considering higher standards. Application consideration for avoiding contamination include:

- Isolating the ballast-piping system. Many present-day ships have a cross-over to fire mains, black and grey water drains, bilge water lines, and cooling-water circuits.
- Maintaining a high level of tank structure integrity. Especially in aging vessels, decrepit tank structures can permit transfer of fluids from adjacent tanks, piping systems running through the tanks, fluids pooling on tank tops, and directly from ambient water through seams or pipe fittings in the vessel's side shell.
- Protecting tank vents. Ballast-tank vents are typically fitted with only a rough screen or a ball check device to minimize seawater entry. Given higher treatment standards, protecting vents from seawater or "bug" entry is of increased importance.

<u>Identifying Key Elements of an Idealized Shore-Side Plant for Treating Ballast Water</u>
In developing new approaches to treating ballast water, the wastewater-treatment industry is an obvious place to turn. This industry has developed methods to disinfect large volumes of water to very high standards for large and small organisms. New approaches adapted from that arena may be very efficacious and achieve the desired higher standards, but will take time to develop, trial, and determine their practicality and cost impacts. Nonetheless, it will be useful, at least as a thought exercise, to consider a shore-based treatment system as an idealized solution. Its operational particulars will form the basis of comparison for the following subsection, which considers new approaches to ballast-water treatment on board a marine vessel.

To that end, we developed a hypothetical design for an onshore-based ballast water treatment plant with a design capacity of 20,000 m^3 of ballast water per day. This is equivalent to ~800 m^3 per hour, roughly similar to a "low ballast dependent" vessel such as a containership. ("High ballast dependent" vessels, such as Great Lakes bulkers and large tank ships, would require a treatment plant five to twelve times larger.) The resulting design requirements for the hypothetical treatment plant were estimated as:

- Equalization tanks of volume 20,000 m^3.
- Plain sedimentation area of ~1,000 m^2.
- Granular media filtration of ~120 m^2.
- Three UV units each at ~800 m^3 per hour.
- Sludge and backwash handling.
- Possibly to include a membrane-filtration unit.

<u>Concepts for Meeting a Higher Ballast-Water Treatment Standard</u>
This section envisages systems whereby both ballast-water management and treatment technologies can meet more stringent standards. These concepts have been developed with

reference to challenges outlined in previous subsections, and with the goal of following the design of the idealized shore-side treatment plant. These approaches will significantly increase the operational burden on ship operators, but are considered to be technically feasible to integrate into new vessel designs. Integrating these systems into existing vessels will be challenging on most, and not possible on many.

These concepts are provided to provide an understanding of the technical and operational demands associated with meeting a higher standard. In addition, these systems and processes need to be defined in order to develop cost-benefit analysis. Cost estimates, capital or operating, have not been developed for these concepts.

>>Overview
Treatment integration is based on utilizing large media filters that are integral to the vessel hull on ballast water uptake and discharge and the ability to re-circulate the ballast water in the ballast water tanks, in order to dose, monitor and maintain an oxidant level in the ballast water tanks. For ballast water discharge a residence tank is considered to ensure neutralization of the oxidant, and a final UV disinfection step through a dedicated ballast water discharge connection. The concept considers volumes for a Panamax container ship, with a ballast volume of 17,000 cubic meters and a discharge rate of 500 cubic meters per hour.

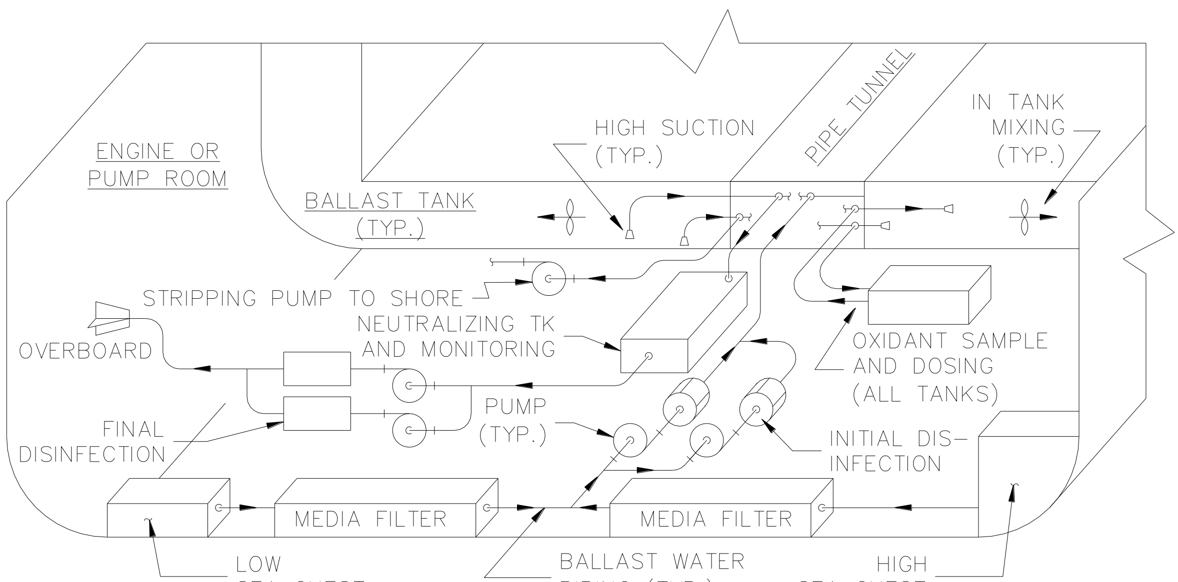

Figure 4.1. – Concept Sketch of New Approach to Ballast Water Treatment

>>Ballast water uptake
Two traditional, but oversized, seachests would serve to take up ballast water. Piping will generally be 300 mm nominal. Each would include standard skin-valve isolation and piping materials. The seachests would be located port and starboard, one high and one low, with a cross-over suction main connecting each. This provides flexibility for avoiding sediment when

the ship is close to the bottom, and algal blooms when the ship is light and the high seachest is close to the surface. Methods of keeping the seachest and adjacent hull areas free of fouling organisms are not considered here.

The cross-over suction main would discharge by gravity into two large media chambers plumbed in parallel and each sized for full flow. This arrangement allows one to be by-passed during back-flush cycles. Each would be built into a one-meter height double bottom in the ship's hull and eight-meters square for a volume of 64 cubic meters each. Industrial waste water industry media with tolerance for velocities approaching 60 meters per hour, and a useful life of six years to last between dry dock periods would be considered. Six-year servicing of media would be through manhole covers.

Ballast water leaving the media filter is disinfected prior to entering the ballast water tanks, either by a UV or an oxidant chemical. This transfer is possible by using ballast water pumps, or through gravity when there is adequate head pressure from the sea. The piping would be direct, through a pipe tunnel for ease of monitoring condition and servicing, and have no cross-connects.

>>In tank
Once a ballast water tank is full or partially full, it would be periodically mixed through the use of low pressure – high volume air bubbles, or in tank educators. This mixing will allow the application of an oxidant to a prescribed level, the monitoring and the maintenance of that oxidant level. Mixing frequency would be based on detected oxidant decay levels, as well as calculations to prevent sediment from settling.

The tanks would be fitted with pressure-vacuum relief valves that only open when the ballast water is being transferred or occasionally to relieve built-up pressure or vacuum from a diurnal cycle. The gauging system would be a other closed system to limit contaminants from entering the tanks. At least two tank vents would be installed. Each vent would be fitted for ready connection to ventilation blowers to facilitate gas freeing tanks to make safe for personnel entry. Depending on the required oxidant level, the ballast tanks may require a special coating system. In addition piping system gaskets and valve seals may require special materials not typically used in seawater applications.

>>Discharge
Each tank would be fitted with piping for deballasting with a high suction at approximately 300 mm above the tank bottom, and a low suction at approximately 75 mm above the tank bottom. The high suction would be used for ballast tank discharge, such that the discharge does not contain sediment. The low suction would be used for stripping sediment from tanks when suitable disposal facilities are available.

The discharge piping would be independent from the uptake piping. Each tank would be outfitted with an isolation valve connecting it to the discharge main header. The header would lead to a reactor tank of one-meter height built into the ship's double bottom with at least twentyfive cubic meters capacity allowing a contact time of at least three minutes. During the contact time, the oxidant level would be neutralized and water quality confirmed prior to discharge. The system would be fail safe, returning the ballast water to the ballast water storage tank if needed. An independent seawater overboard of standard construction would be fitted for discharging the ballast water. As close as practical to the overboard, a final UV disinfection step would be considered. This final disinfection step would provide assurance against contaminants in the reactor tank where the oxidant was neutralized, as well as a measure of caution in treating the ballast water a second time by a different process.

The ballast water may be moved through the discharge by gravity if there is adequate head in the ballast tank. At any time, a pump would take suction on the reactor tank, avoiding pump contact with the oxidants. The pump would then discharge to the UV unit and overboard.

>>Summary
The above arrangement is presented as a concept for meeting higher standards through higher filtration levels, greater control of oxidant levels in tanks, and a final disinfection using UV radiation. This conceptual process has not undergone any biological efficacy testing or toxicity analysis. It is presented solely to assist in the evaluation of how higher treatment standards might impact vessel arrangements, operations, and costs.

Charge question 3b. Part a. *What are the principal technological constraints or other impediments to the development of ballast water treatment technologies for use onboard vessels to reliably meet any or all of the discharge standards presented in Table 1 of the White Paper and what recommendations does the SAB have for addressing these impediments/constraints?*

Response:
We list here principal constraints and impediments.

- Ship-board ballast water treatment technologies are developing rapidly. The focus to date has been on engineering the technology. Less consideration has been given to the following, which are equally important: training, operation, maintenance and repair, and monitoring effectiveness.
- With regard to monitoring effectiveness, zero live organisms in the discharge is an unrealistic and unattainable goal. The complexity of the systems and the difficulties associated with counting live organisms, particularly the smaller size classes, combine to limit our ability to measure improvements to levels 100X and 1000X IMO. Facilities at which technologies may be tested are few, and there is a strong need to increase sharing of data and specific protocols among them.
- There is no established compliance, monitoring and enforcement regime which will focus development of future technologies. To our knowledge, none such is envisioned.
- There is disagreement on discharge standards; they vary domestically, i.e., from state to state within the USA, and internationally.

Despite the constraints listed above, we note that successful systems will, as described by Glosten (2002):
1) meet the demands of the shipboard marine environment
2) minimize operational changes to the vessel's existing ballast management systems
3) fit within the normal and existing operational procedures of shipboard personnel
4) minimize initial capital and life-cycle costs
5) meet the existing safety standards of the industry, regulatory bodies and the target vessel operating company.

In the context of recommendations, we expand briefly on these points below.

- The shipboard marine environment is corrosive and characterized by vibrations and ship motions. One should not assume shore-side systems can transfer straightforwardly to ships. Shipboard service history will be important in selecting system components. Even so, the characteristics of water in some shipboard applications may differ from those of ballast water, e.g., the amount of sediment in ballast water may be greater, thus prediction of system performance based on service history may be challenging.

- Vessels are initially designed with ballasting capabilities and procedures that match their intended service and voyage profile. In retrofitting vessels for ballast-water treatment, the system(s) employed ideally will fit within those original parameters and minimize disruption.

- Ships' crews are small in number and busy; therefore, any new system must be easy to operate, maintain, and ideally be remote controlled from the ballast-control console. It is also desirable to have automated operation of the system in or near port, typically a busy time for personnel. And in the same vein, durability and ease of maintenance are requisites.

- A treatment system's full cost includes not only its initial purchase and installation, but its operational costs over the long term as well. System reliability, durability, cost of spares, and ease of maintenance, e.g., filter element or bulb replacement, all contribute to the desired minimization of these long-term costs.

- Most importantly, the treatment system should pose no unreasonable health risk for the crew, not create a higher risk for vessel safety, and require no exception to the vessel owner's safety procedures. The equipment installation and operation procedures must also meet Classification Society, Flag State, and Port State control authorities' requirements.

Finally, Subgroup 2 makes the overall recommendation that shipboard constraints to ballast-water treatment technology need to be considered relative to potential increased usage of shore-based treatment facilities (see also response to charge question 4).

Charge question 3b. Part b. *Are these impediments more significant for certain size classes or types of organisms (e.g., zooplankton versus viruses)?*

Can currently available treatment processes reliably achieve sterilization (no living organisms or viable viruses) of ballast water onboard vessels or, at a minimum, achieve zero or near zero discharge for certain organism size classes or types?

Response: Shipboard impediments apply equally to all size classes or types of organisms. Existing systems, or combinations of systems, are capable of removing (e.g., filtration) or killing (e.g., deoxygenation, UV, chlorine dioxide) all or nearly all organisms > 50 µm in minimum dimension. Pragmatically, it may be best to focus on eliminating larger organisms in ballast water as completely as reasonably possible, then assessing the extent to which smaller organisms (e.g., bacteria, viruses) survive the treatment and direct reasonable resources to reduce their numbers.

If ballast water were sterile, it would be "free from living organisms and viruses" (Madigan and Martinko, 2006). Given the volumes of water involved, our subgroup maintains that onboard sterilization of ballast water is not possible given current technologies. There simply isn't enough energy on a ship to implement steam autoclaving. Further, as a practical matter, the assurance of sterilization is impossible to verify if the methodology for collecting organisms and assessing their viability is variable or uncertain (these issues are considered in response to charge question 4).

Charge question 3b. continues: "If not sterilization, then is it possible to achieve zero or near-zero discharge for certain organism size classes or types?" As indicated above, we believe the technology exists to remove all or nearly all organisms ≥50 µm (minimum dimension) from discharged water. Whether that degree of removal could be proved through measurements (quantitative sampling for statistical verification), especially at full-scale testing or operation, is another issue. Subgroup 7 (Cross-cutting group on statistics) has considered the limits of detection and concluded there is no assurance of zero or near-zero discharge. Our subgroup concurs. Such a value is not measureable in a scientifically defensible way and instead represents a social preference. No one in the fields of toxicology or waste-water treatment, disciplines represented within our subgroup, believes that such a goal is realistically achievable in the real world; it is an unreasonable requirement and should be reconsidered as a ballast-water treatment standard. The problems with zero or near-zero discharge amplify when smaller organisms are considered, those <50 micrometers in shortest dimension, e.g., phytoplankton, bacteria, and viruses.

Finally, while "zero or near zero discharge" may theoretically be achievable (and arguably even measurable) at a test facility, it will never be obtained or verified at "end of pipe" for a working ship. The water in the tank might be "clean", but it will flow through piping which will not be. Particularly with non-biocide units, we anticipate there will always be pipe dead ends, crosses, etc., where organisms can find refuge, then emerge and be detected during testing. We have named this the paradox of "perfect systems on imperfect ships".

The current filter and disinfect approach may not be adequate to meet more stringent standards. Treatment processes will need to become multistage and part of an integrated ballast water management effort (see response to charge question 4). Meeting increasingly stringent performance standards will require that BWT systems perform nearly perfectly, nearly all of the time. Existing ship ballast water management systems and practices do not support this level of control nor performance; a fundamental shift in system design and operational practices would be needed.

Reliability is a key metric that is not captured in the current certification-focused testing regime. A well defined compliance, monitoring, and enforcement regime is required so that system engineers can target those metrics, rather than be focused primarily on a certification test.

REFERENCES:

Design Study Report, Full-Scale Design Studies of Ballast Water Treatment Systems, prepared for Northeast Midwest Institute, Glosten – Herbert – Hyde, April 2002.

Madigan, M.T., and J.M. Martinko. 2006. Biology of Microorganisms, 11th ed. p. G-14.

(definition of “microorganism” on p. G-9)

EPA SAB Ballast Water Advisory
Subgroup 2

SECTION 5: Draft Response to charge question 4:
Limitations of existing studies and reports

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I. Introduction

A. Charge from EPA and the Focus of this Document

This section responds to Charge Question 4: *"What are the principal limitations of the available studies and reports on the status of ballast water treatment technology and system performance and how can these limitations be overcome or corrected in future assessments of the availability of technology for treating ballast water onboard vessels?"* Charge question 4 (and the preceding charge questions 1 through 3) are under the committee's overall charge to "provide advice on technologies and systems to minimize the impacts of invasive species in vessel ballast water discharge" (Feb. 2010 Federal Register notice). While we address Charge Question 4, we also address aspects of the broader charge not covered by any of the four specific charge questions. Specifically, in later sections of this report, we address limitations of technology and systems to enable effective compliance and enforcement, and on-shore treatment systems.

II. Testing Shipboard Treatment Systems: Protocols, Analysis, and Reporting Practices that Could be Improved

A. Lack of Independent Testing

Testing should be conducted by a party independent from the manufacturer with appropriate, established credentials, approved by EPA/USCG.

To ensure that the performance of ballast water treatment systems is objectively and thoroughly evaluated, experienced specialists in an independent testing organization should conduct the tests, rather than the system manufacturers. This is important because science has shown that it is extremely difficult, after the creator of a system has been constructively designing it, to change h/her perspective and instead approach the treatment system from a "deconstructive" state of mind to form the necessary mental attitude of wanting to find flaws and expose weaknesses and limitations (Myers 1979). Thus, verification testing conducted by independent specialists is critical in accomplishing a scientifically rigorous assessment of system performance. The testing organization should provide detailed information about the expertise of its personnel, and the established credentials of these personnel should be approved by the U.S. EPA/USCG.

B. Lack of Standardized Testing Protocols

Comparison of the performance of different ballast water treatment technologies requires consistent testing protocols (Phillips 2006, Ruiz et al. 2006). Except for the ETV protocol (U.S.

EPA 2010), which is in final clearance, there is no comprehensive international, federal or state program that includes performance standards, guidelines, and protocols to verify treatment technology performance, and no standardized sets of methods for sampling and analysis of ballast water to assess compliance. The existing federal and various state standards lack consistency as well. Treatment evaluations generally are designed to test whether a given technology can meet International Maritime Organization (IMO) D2 standards in accordance with both the IMO *Guidelines for Approval of Ballast Water Management Systems* (G8) and the *Procedure for Approval of Ballast Water Systems that Make Use of Active Substances* (G9) (IMO 2008a,b

With exception of the U.S. Coast Guard's (USCG's) Shipboard Technology Evaluation Program (STEP), ballast water treatment systems at present are not approved for use in compliance with federal ballast water management requirements. Thus, while there are various state ballast water management requirements, there is no formal environmental assessment approval program for ballast water treatment systems at the federal level. US EPA has, however, included provisions in the draft NPDES Vessel General Permit for ships with treatment systems that discharge ballast water containing biocides or chemical residues. In addition, US EPA's Environmental Technology Verification (ETV) Program was created to accelerate the development and marketing of environmental technologies including ballast water treatment, and recently developed a treatment technology verification protocol that is available in draft form (U.S. EPA 2010). Protocols in the IMO G-8 Guidelines, supported by the new U.S. EPA Environmental Technology Verification (ETV) Program (U.S. EPA 2010), specify taking whole-water samples of at least 1 m^3 (1,000 L) for organisms greater than 50 µm, and at least 1 m^3 for organisms greater than 10 µm but less than or equal to 50 µm.The state of California also has developed "Ballast Water Treatment Technology Testing Guidelines" that are intended to provide a standardized approach for evaluating treatment system performance (Dobroski et al. 2009). Procedures are being developed for verifying vessel compliance with performance standards as well.

Performance standards set requirements for technology to achieve and should help to advance progress in treatment system designs, but only if a set of standardized, practical, scientifically rigorous assessment techniques is available to evaluate treatment system performance. The IMO standards are based upon different size groups of organisms, and the small size groups are especially problematic in efforts to assess performance (see below). Assessment has relied upon a subset or "surrogate" group of organisms as representative of treatment of all bacteria (see Section 2. C, below). There is as yet no strong evidence for suitable proxy organisms to represent the virus size class, and no acceptable methods for verification of compliance with a total virus standard.

The following analysis summarizes the ETV recommendations but focuses on differences between the SAB's recommendations and the recently developed ETV protocols (U.S. EPA 2010). Both the ETV protocols and the SAB recommendations feature land-based rather than shipboard testing to provide comparable conditions for verifying treatment performance by independent testing operations.

1) Test Verification Factors

All treatment systems should be verified considering the following factors: biological treatment efficacy, operation and maintenance (OM), reliability as measured by the mean time between failure (MTBF), cost factors, environmental acceptability including residual toxicity, and safety. ETV and SAB agree that biological treatment efficiency (the removal, inactivation, or death of organisms) should be measured as the concentration, in the treated ballast water discharge, of the organism size classes indicated in the IMO standard, comparing the untreated versus treated ballast water. Other measurements can include organism removal efficiency (the percentage reduction of organisms that were present in the untreated ballast water), and water quality parameters in comparison to appropriate water quality standards. Verification protocols should include detailed descriptions of on-site sampling, sample handling (chain of custody), in-place mechanisms for selecting independent laboratories with appropriate expertise and certification to conduct the sample analyses, and requirements for compliance reporting.

ETV and SAB agree that tests and species selected for toxicity testing during commissioning need to be carefully justified and protocols detailed in the Test Plan. BWTSs that involve a chemical mode of action are regulated under the National Pollutant Discharge Elimination System (NPDES) permit process (Albert et al. 2010), which requires demonstration of "no adverse effects" as evaluated through chemical-specific parameters and standardized Whole Effluent Toxicity (WET) testing (U.S. EPA 2002a-c; 40 CFR 136.3, Table 1A). WET experiments are designed to assess the effects of any residual toxicity on beneficial organisms in receiving waters. Standardized acute and chronic toxicity assays have been developed by the U.S. EPA for a limited number of freshwater and marine species (Table 2). The ETV did not comment on the freshwater assays, but recommended that toxicity tests for biocide treatments in brackish and marine waters should include the U.S. EPA acute toxicity assay for mysids (EPA OPPTS Method 850.1035; http://www.epa.gov/opptsfrs/OPPTS_Harmonized/850_ Ecological_Effects_ Test_Guidelines/Drafts/850-1035.pdf, and the chronic toxicity assays for the inland silverside,*Menidiaberyllina*(larval survival and growth, EPA Method 1006.0; http://www.epa.gov /OST/WET/disk1/ ctm13.pdf) and the sea urchin, *Arbaciapunctulata* (fertilization, EPA Method 1008.0; http://www.epa.gov /OST/WET/disk1/ctm15.pdf). SAB recommends that freshwater assays also be included in toxicity testing.

Table 2. Freshwater and marine species for which the U.S. EPA has developed standardized acute

Table 2. Freshwater and marine species for which the U.S. EPA has developed standardized acute and chronic toxicity assays (http://www.epa.gov/waterscience/WET).[1]

Habitat	Acute Toxicity	Chronic Toxicity
Freshwaters		
Algae	---	*Selenastrumcapricornutum* (growth)
Zooplankton	*Ceriodaphniadubia*	Survival, reproduction
	Daphnia magna	---
	Daphnia puplex	---
Fish	Bannerfin shiner (*Cyprinellaleedsi*)	---
	Brook trout (*Salvelinusfontinalis*)	---
	Fathead minnow (*Pimephalespromelas*)	Larval survival, growth; embryo-larval survival, teratogenicity
	Rainbow trout (*Oncorhynchusmykiss*)	---
Marine		
Mysid shrimp	*Americamysisbahia*	Survival, growth, fecundity
Sea urchin	---	*Arbaciapunctulata* - fertilization
Fish	Sheepshead minnow (*Cyprinodon variegatus*)	Larval survival, growth; embryo-larval survival, teratogenicity
	Silversides (*Menidiaberyllina, M. menidia, M. peninsulae*)	*M. beryllina*- larval survival, growth

Complete results including failures should be reported as standard practice. These data are needed to enable realistic evaluation of a given ballast water treatment system. At present, there is no requirement under IMO to report tests in which a treatment system fails. Rather, for type testing success, a system must report only a specified number of successful tests. The SAB strongly recommends that reports should include all failed and successful tests, and that criteria for approval should consider the failure rate (proportion of tests that were successful).

2) Challenge Conditions

In contrast to the ETV, the SAB recommendas that testing should be applied across the full gradient of environmental conditions represented by the Earth's ports (Table 3). All treatment technologies should function well across the range of physical/chemical conditions and densities/types of biological organisms that a ship encounters. Thus, ballast water treatment systems should be verified using a set of standard challenge conditions that ideally encompass the suite of water quality conditions which captures the full gradient of environmental conditions represented by major ports, and the range of densities of the organisms and organism size classes.

The ETV states that the objectives for challenge conditions are to verify treatment system performance using a set of "challenging, but not rare, water quality conditions representative of the natural environment;" and to verify removal or kill of organisms ranging in size from bacteria to zooplankton, using natural assemblages and appropriate analytical techniques that enable quantification of densities of live organisms (U.S. EPA 2010, p.19). In contrast the SAB believes it is important to evaluate the effectiveness of treatment systems under conditions that challenge the technology because certain water quality conditions can interfere with some treatment processes. These physical/chemical environmental conditions are generally understood and relatively few in number, which helps to limit the number of water quality metrics that must be included in the protocol (Table 3).

Table 3. Comparison of the ETV's recommendations (U.S. EPA 2010) and the SAB's recommendations, considering minimum criteria for challenge water total living populations, criteria for a valid BE test cycle (living organisms in control tank discharge after a holding time of 1 day), and water types (salinity groupings) for completion of BE tests.

Minimum Criteria for Challenge Water Total Living Populations; and
Criteria for a Valid BE Test Cycle - Living Organisms in Control Tank Discharge After 1 Day Holding Time

Size Category	ETV	SAB
≥ 50 µm	10^5 organisms m^{-3}, 5 species in 3 phyla	same
≥ 10 µm and < 50 µm	10^3 organisms mL^{-1}, 5 species in 3 phyla	same
Other[3]	< 10 µm: 5 x 10^2 mL^{-1} as culturable aerobic heterotrophic bacteria	≥ 2 µm and < 10 µm: 10^3 organisms mL^{-1} < 2 µm: same as ETV for < 10 µm

Water Types (Salinity Groupings) for Completion of BE Tests[4]

Fresh (salinity < 1) Brackish (salinity 1 to < 28) Marine (salinity > 28)	At least two salinity ranges	All three salinity ranges

[1] Size considers the maximum dimension on the smallest axis.

[2] Effects on culturable aerobic heterotrophic bacteria are assumed to be indicative of effects on all bacteria.

[3] "Global diversity of bacteria" by species or phyla is not applicable; there is no diversity requirement for this size class.

The ETV (U.S. EPA 2010, p.30) recommends completion of BWT tests in at least two of the three salinity ranges (Table 3). The SAB recommends, instead, that the testing should include all three ranges for systems intended for use across the salinity gradient from fresh to marine waters. Our rationale is that if a given ballast water treatment system is planned for use across the salinity gradient, but testing indicates that its efficiency at organism removal is poor under one or more of the salinity groupings, then that system should not be used by ships visiting ports that are characterized by such conditions. Similarly, if a ballast water treatment system is planned for use across other environmental gradients (e.g. temperatures from cold to warm waters), but tests indicate that it has poor efficiency in removing biota under part of the natural temperature range, then that system should not be used by ships visiting ports that have such conditions.

There are major practical constraints on such tests. First, alterations to establish the natural range of physical/chemical conditions should be imposed without affecting the concentrations, diversity, and viability of the biota present. For that reason, natural water sources should be used to impose the three levels of salinity recommended, rather than artificially modified salinity. Artifactual interactions may occur between biota and artificial media, for example, artificial seawater prepared with commercially available "sea salts." The SAB thus diverges from Anderson et al. (2008) in recommending that a source of filtered, high-quality natural freshwater or seawater should be used to prepare treatments insofar as possible. There are pros and cons with either approach: Artificial sea salts are expensive but enable routine preparation of media. However, caution is warranted in using artificial sea salts because some ingredients that are not found in natural seawater, such as phthalicesters(e.g. di(2-ethylhexyl)phthalate, a commonly used plasticizer in Instant Ocean aquarium salts), are abundant and can be toxic to aquatic life, resulting in spurious data (e.g. Peal 1975, Moeller et al. 2001). Various dissolved organic compounds that are important to the nutrition and the life histories of aquatic organisms (see Burkholder et al. 2008) likely will be missing from artificially constructed media. While use of natural waters avoids such problems, the natural water source should be free from toxic pollutants, which are increasingly ubiquitous in fresh, brackish, and coastal marine waters (Kay 1985, Pate et al. 1992, Loganathan and Kannan 1994, Hoff et al.1996, U.S. EPA 2000, Shaw and Kurunthachalam 2009). Final selection of an artificial versus available natural water sources requires careful consideration of these issues.

The ETV recommends adjusting POM by adding commercially available humic materials, plankton, detritus, or ground seaweed; commercially available clays can be added to adjust the MM concentration (U.S. EPA 2010). However the SAB is concerned that the cation exchange capacity of the dried, then rehydrated clays can significantly alter plankton communities (Avnimelech et al. 1982,Burkholder 1992, Cuker and Hudson 1992). Artificial modification of DOC is difficult to achieve without a strong potential of affecting the biota present, especially the smaller size-fraction components. The SAB believes that the testing organization should be required to verify, insofar as possible, that in preparing the test water, any materials added had minimal affects on the biota, and "minimal effects" should be clearly defined.

The IMO (2008a,b), the ETV (U.S. EPA 2010), and other suggested standards (e.g. California VGP 401 certification/State regulations (see Albert et al. 2010) make no mention of organisms in the 2 to < 10 µm size range. Many harmful organisms occur in this size range (e.g. harmful "brown tide" pelagophytes*Aureococcus* and *Aureoumbra*, many harmful cyanobacteria, certain potentially toxic dinoflagellates etc. - see Burkholder 1998, 2009). The selected bacteria presently targeted for standards are not useful as indicators for the presence of these taxa which, as a general grouping, can adversely affect both environmental and human health (Burkholder 1998, 2009). Thus, failure to consider this size class represents a serious omission in efforts to protect U.S. coastal estuarine/marine waters and the Great Lakes from harmful invasive species introductions. For some of these taxa, such as toxigenic *Microcystis* spp. affecting the Great Lakes (e.g. Boyer 2007), the tendency of the cells to aggregate into colonies effectively "boosts" them into the >10 µm size class, but for others such as the brown tide organisms, such aggregation does not occur. There is a critical need to include this size class, or at a minimum, harmful representatives from it (which should be expected to vary depending on the geographic region) in developing protective ballast water standards. Accordingly, this size class should be included in standards for assessing the performance of BWTSs.

B. 4) Verification Testing

The SAB differs from theETV on some protocols, including specifics for collecting water quality and biological samples in performance testing of BWTSs (Table 4). For zooplankton, phytoplankton and other protists, the SAB supports the need for collecting at least 3-6 m^3 of sample volume at each required location on a time-averaged basis over the testing period. Field quality control samples and field blanks should be taken under actual field conditions to provide information on the potential for bias from problems with sample collection, processing, shipping, and analysis (Ruiz et al. 1996). Accepted scientific methods should be used for all analyses (e.g. for water quality parameters, U.S. EPA 1993, 1997; American Public Health Association (APHA) et al. 2008). Biological samples should be collected from the time-integrated sample volumes during the test cycle; sample collection tanks should be thoroughly mixed prior to sampling to ensure homogeneity. Samples collected from control and treated tank discharges should be taken upstream from pumps or other apparati that could cause mortality or other alterations. Note that analysis of some parameters is extremely time-sensitive (Table 4).

For example, zooplankton die-off occurs in samples held for 6 hours or more. The approximate maximum hold times should maintain detectable zooplankton mortality over time at $\leq$ 5%. As a more practical alternative than attempting to quantify viable organisms from unpreserved samples, the SAB recommends preserving samples immediately upon collection and then assessing intact organisms as “viable when collected,” based on the fact that zooplankton are known to decompose rapidly after death (minutes to several hours) (Johnson and Allen 2005).

Table 4. Sample volumes, containers, and processing for core parameters and auxiliary nutrients (nitrogen, N; phosphorus, P; silicate, Si; carbon, C). Note that HDPE ≡ high-density polyethylene, and POC information is from Baldino (1995). Recommendations that differ from those in the ETV (U.S. EPA 2010) are indicated in **bold**.

Parameter	Minimum Sample Volume	Containers	Processing/Preservation Holding Time	Maximum
TSS	100 mL	HDPE or glass	Process immediately or store at 4^{o}C	1 week
DOC	25 mL	glass	Pre-combusted GF/F filters; **preserve filtrate with H_3PO_4 (pH < 2), hold at 4^{o} in darkness (APHA et al. 2008)**	28 days
POC	500 mL	HDPE	Filter (GF/F in foil); freeze filter until analysis	28 days
MM (need to add)				
DO	**300 mL** **or** *in situ* sensor	**glass BOD bottles**	Fix (Oudot et al. 1988); titrate in 2-24 hours; or Continuously recording	24 hours
Chlorophyll *a*,[1] pheopigments	400 mL	dark HDPE	Filter (GF/F); fix with saturated $MgCO_3$ solution; freeze filter until analysis	3 weeks
Phytoplankton No.[2] (viable, 2 to < 10 µm)	**500 mL**	**dark HDPE**	**Filter (Nuclepore or Anotech); assess autofluorescence (e.g. MacIsaac and Stockner 1993), <u>or</u>** **Filter, fix (e.g. 0.2% (v/v) formalin), freeze filter; <u>or</u>** **filter, fix, followed by selected molecular techniques (e.g. Burkholder et al. 2007)**	**process immediately** **3-4 weeks** **months**
Phytoplankton # (viable, nano-/ micro-plankton)[3]	3 m^3 (1,000 L) → 1 L	60 mL dark HDPE	Viable: No preservative; stain with FDA, CMFDA;**<u>or,</u>** **fix with acidic Lugol's solution (Vollenweider 1974), store at 4^{o}C in darkness, and quantify as viable when collected (formerly viable), <u>and</u> combine with various molecular techniques to confirm harmful taxa of interest (e.g. Burkholder et al. 2007)**	process immediately **28 days, preferably 1 week**
Other protists (#) (viable heterotrophs)	**3 m^3 (1,000 L) → 1 L**	**100 mL, dark HDPE**	**No preservative; most probable number (MPN) from Anderson et al. (2008); other methods adapted from Petterson et al. (2007); <u>or</u>**	**process immediately**

Table 4, cont'd.

Parameter	Minimum Sample Volume	Containers	Processing/Preservation Holding Time	Maximum
Other protists (#) (viable heterotrophs) (cont'd.)	**$3\ m^3$ (1,000 L) → 1 L**	**100 mL, dark HDPE**	**Filter, freeze, fix as in Sherr and Sherr (1993); <u>or</u> fix, filter, stain (e.g. Sherr et al. 1993, Montagnes and Lynn 1993)**	**weeks to months**
Zooplankton # (viable)	$3\ m^3$ (3,000 L) [3] → 1 L	1-L flask	No preservative; subsample 450 1-mL wells[3] and probe; **fix with buffered formalin and Rose Bengal's solution to quantify; <u>or</u> fix as above and quantify as formerly viable (Johnson and Allen 2005)**	Process immediately (< 6 hr) [4] **Process within 1 month**
Bacteria (active culturable, selected taxa)	$\geq$ 500 mL [5] [1 mL to 500 L]	sterile HDPE	Plate on appropriate media (add references)	Process Immediately (< 6 hr; or 1-5 days)
Nutrients[1] - TN, TP total Kjeldahl N (TKN)	**60 mL**	**polyethylene**	**Preserve with H_2SO_4 (pH < 2), hold at 4^oC in darkness (U.S. EPA 1993, 1997; APHA et al. 2008)**	**28 days**
NO_xN, NH_xN,SRP, Si	**60 mL**	**polyethylene**	**Filter and preserve/hold (U.S. EPA 1993, 1997; APHA et al.2008)**	**28 days**

[1] *In situ* sensors are available for measuring chlorophyll *a* as relative fluorescence units, but not as chlorophyll *a* concentrations. Chlorophyll *a* may be considered as a core parameter or as an auxiliary parameter, used as a collective indicator for algal biomass. The SAB also recommends assessment of nutrients if possible, although nutrients are not considered as core parameters by the ETV.

[2] This size category has not been considered for ballast water treatment standards by IMO (2008a,b), the ETV etc. Because many harmful organisms occur in the 0.2 to < 10 µm grouping,this size class should be included in assessment of BWTSs.

[3] FDA, fluorescein diacetate; CMFDA, 5-chloromethylfluorescein. Delicate protists (e.g. wall-less flagellates) mostly would not be expected to survive the process of rapid concentration of large-volume samples. As a much more practical alternative than attempting to quantify viable algae and other protists from unpreserved samples, the SAB recommends preserving samples immediately upon collection and then assessing intact organisms as "viable when collected," based on the fact that protists such as most algae in this general size class are known to lyse and/or decompose rapidly (minutes to several hours) after death, so that the cell contents become distorted or are lost even if the cell coverings remain (Wetzel 2001).

[3] The ETV recommends a sample size for the zooplankton size class of at least $1\ m^3$ (1,000 L), concentrated to 1 L, and analysis of 20 subsamples. However, microbead experiments conducted under "best case" conditions by the Naval Research Laboratory (Lemieux et al. 2010) indicated that the ETV protocol will not achieve acceptable precision.

[4] Zooplankton die-off occurs in samples held for 6 hours or more.

[5] The volumes used to quantify bacteria vary widely; as examples, the ETV recommends techniques that use as little as 1 mL, whereas MERC (2009c) uses 500 L. Since bacteria generally are abundant, the SAB recommends use of 500 mL.

C. Compromises Necessary Because of Practical Constraints in Sampling and Available Methods

The ideal goal of standard challenge conditions that include the full (a) gradient of conditions present in theworld's ports, (b) range of organism density, (c) range of taxonomic diversity, and (d) range of organism size classes is impeded by several serious practical constraints in sampling large ballast tanks effectively, and in the methods that presently are available for quantifying viable organisms. As Lee et al. (2010, p.19) pointed out, "perfect compliance and no failure is practically, if not theoretically, impossible, particularly for microbiological organisms unless ballast water is discharged into a land-based treatment facility or ships are redesigned to eliminate the need to discharge ballast water." This section considers how the ideal can be modified to accommodate practical considerations while accomplishing a meaningful evaluation of the efficacy of ballast water treatment systems.

1) Standardization of Choices of Test Organisms (Surrogate Species)

ETV defines standard test organisms, or surrogates, as "organisms of known types and abundance that have been previously evaluated for their level of resistance to physical and/or chemical stressors representing ballast water technology,…added to the challenge water during testing…to determine treatment system effectiveness" (U.S. EPA 2010, p.xi). Post-treatment viability of surrogate taxa or life history stages is often used to evaluate the biological effectiveness of ballast water treatment systems in removing zooplankton, protists (heterotrophic and phototrophic), and bacteria. The SAB urges caution, however, since results from a very small number of taxa are broadly applied to all of the organisms in the same general grouping (e.g. protozoans in a certain size class). An assumption that first must be validated is that the selected taxa are among the most resistant to treatment, so that most organisms are eliminated when the surrogate taxa are eliminated (Ruiz et al. 1996). The fundamental challenge is to identify the best species that are "representative" of a broad range of organisms within a given size class. Good candidates are considered to be easily and economically cultured in large numbers for future full-scale testing in experimental ballast water tanks, tolerant of a wide range of environmental conditions, reliable and consistent in their response to treatment across culture batches, and resilient in withstanding ballast water tests and sampling (Ruiz et al. 1996, Anderson et al. 2008). An obvious risk is spurious results from surrogate taxa that poorly represent the larger group of organisms.

Given the limitations of present methodologies in assessing the performance of BWTSs, there is a practical need for standardized protocols involving use of surrogate taxa. These protocols should include clear justification for use of surrogate taxa under a defined set of conditions; careful consideration of potential confounding interactions between the surrogates and natural species; and the percentage ratio of challenge organisms that are surrogates versus naturally occurring taxa in the challenge water. Selection of a specific combination of surrogates needs to be based upon extensive testing at bench and mesocosm scales, preferably by several laboratories located in different geographic regions, of a wide range of surrogate species, life histories, habitats, and source regions across environmental gradients (Ruiz et al. 1996). Consistent use of the same protocols is needed in order to minimize confounding factors and strengthen comparability. Ideally, several surrogate species or taxonomic subgroups, including several life stages, should be included in the tests, since confidence in interpretations can be strengthened by this redundancy. It would also be best to include multiple strains (populations) of candidate surrogate species if possible, to account for significant intraspecific variability in response to environmental conditions that is commonly documented, particularly among protists (Ruiz et al. 1996, Burkholder and Gilbert 2006).

2) Standardization of Choices of Indirect Metrics(Surrogate Parameters)

Given the practical/logistical limitations involved in obtaining statistically meaningful estimates of specific numbers of specific organisms per unit volume, as required or proposed in rules, it is tempting to instead focus on parameters that are much more rapidly and easily assessed. Examples of such "surrogate parameters" are discussed here. They can be calibrated with organism numbers in laboratory tests on microcosm "ecosystems," but would be much more difficult, if not impractical, to calibrate for use with unknown types and numbers of organisms in ballast tanks. As an overall caution, there is a critical need to carefully calibrate all potential surrogate parameters(e.g., presence or abundance of taxon-specific DNA or RNA, algal pigments, adenylates, electron accepter colometriccompounds)with natural populations of ballast water flora and fauna before they can be used to evaluate the performance of BWTSs – especially at the resolution of very low organism densities.

3) Increased use of Tests at Multiple Spatial Scales

Instead of relying solely on full ship-scale testing, the SAB recommends for practical reasons that testing be conducted at a combination of scales, as needed to address particular issues. For example, full-scale tests can pose extreme practical and logistical limitations and/or high risk in efforts to assess the effectiveness of treatment systems in removing maximal densities of harmful organisms, or mixes of representative organisms within certain density ranges. These risks support the use of sized-down treatments that are larger and therefore more realistic than bench-scale microcosms, but more manageable in volume than ballast tanks. Sized-down treatments help to reduce risks to human health safety and receiving aquatic ecosystems for testing treatment system effectiveness at removing toxic substances and residues that are part of the treatment process. As Ruiz et al. (1996) stated, "Economy of small scale and ease of manipulating environmental variables and community assemblage at the laboratory and intermediate scales make it possible and practical to estimate if a ballast water treatment process and system is likely to be effective over the full range of physical [, chemical,] and biological conditions expected in the field;…the same regime on a ship would prove logistically and financially very unwieldy. Thus, smaller scale tests demonstrate the treatment's performance and capacity across a wide range of relevant state variables…." This approach also allows more precise, controlled sampling during test trials (MERC 2009d). At larger scales, practical limitations restrict the number of conditions that can reasonably be tested, and testing is directed more toward ensuring functionality of the engineered system rather than understanding the treatment process under various conditions.

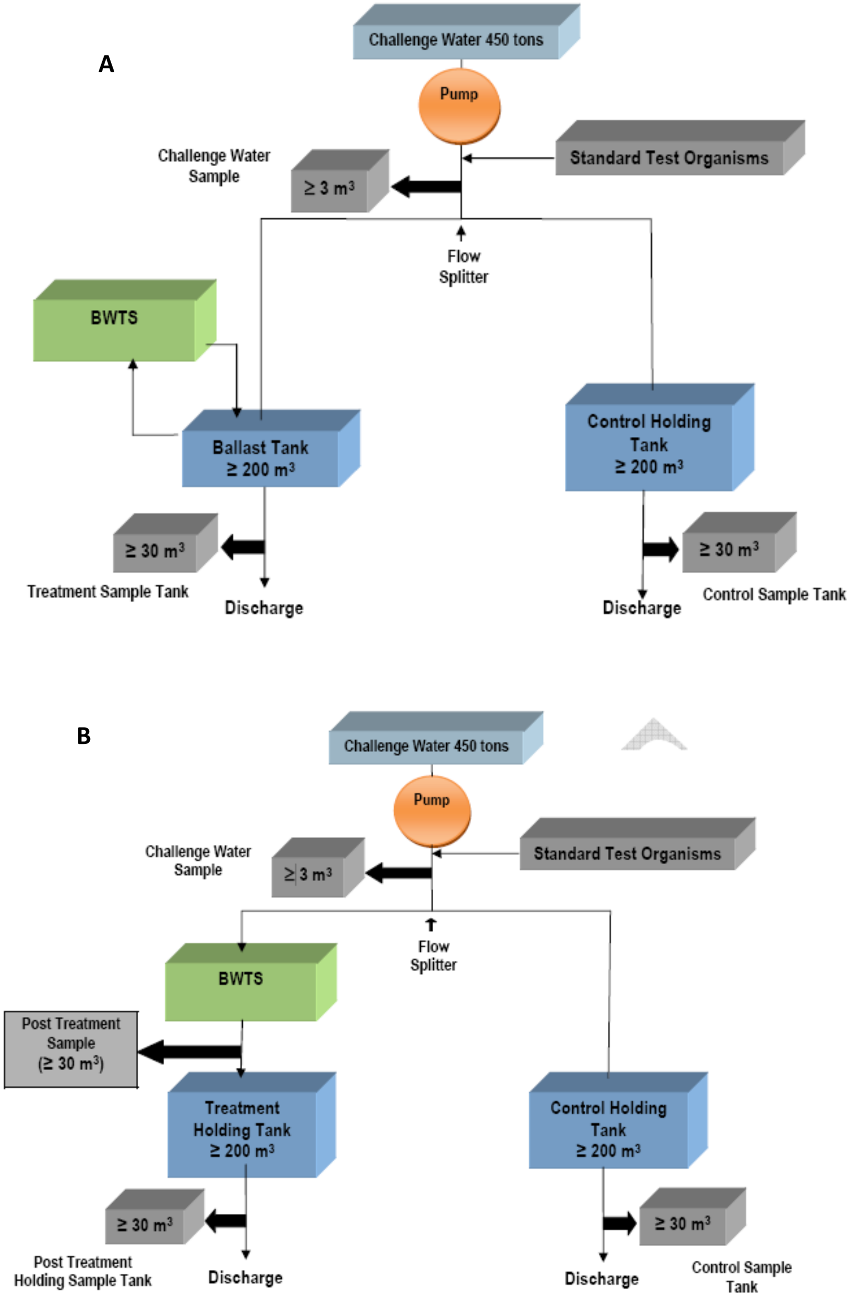

Figure 1.Sampling design example for (A) In-Tank treatment and (B) In-Line treatment.From ETV (2010

Small-scale (benchtop or laboratory) experiments minimize logistics and expense, and they can provide proof of concept in assessing whether a given treatment meets expectations (Ruiz et al. 1996). For example, if a ballast water treatment system is planned for use across the salinity gradient, then its efficacy should be tested across all three salinity ranges (Table 3). Logistically, however, it may feasible to test two salinity ranges at full scale, but not the third. In such cases, small scale and intermediate scale (see below) tests could be completed using the third salinity range. Likewise the SAB recommends that bench-top and mesocosm experiments complement full-scale testing.

III. Testing Shipboard Treatment Systems: Inherent Mismatch Between Viability Standard and Practical Protocols

In the previous section, we reviewed features of current procedures for testing ballast water treatment systems that could be improved with existing knowledge and technology. In this section, we review additional aspects of current procedures that may not really accomplish the stated goals because of inherent limitations in current knowledge and technology. All of the six issues we consider below stem from the difficulty—perhaps the impossibility, given current technology—of accurately enumerating only those organisms that are viable (alive). Current practices result from trying to directly assess the legal standards (which focus on concentrations of viable organisms). The SAB recommends that fresh approaches be considered, including procedures that address the standards indirectly, but have the benefit of practicality. In general, the SAB recommends that the limitations of testing protocols for determining "viability" and/or "living" must be assessed and overcome with new standardized protocols, including indirect metrics that have known correlations with the concentration of viable organisms.

Should subsection 1) below (on the concentration of samples killing organisms) be moved to III.A above, as an issue complicating "the premise that the samples realistically represent the actual concentrations of organisms discharged"?

As Lee et al. (2010, p. 72) aptly state, *"A discharge standard of 'zero detectable organisms' may **appear*** [emphasis added] *very protective; however, the true degree of protection depends on the sampling protocol."* Here, a viable or living organism is defined as in U.S. EPA (1999), namely, as an organism that has the ability to pass genetic material on to the next generation. The percentage of non-viable cells varies markedly, for example, from 5-60% among phytoplankton taxa, and in general, non-viable organisms are believed to represent a substantial component of the total plankton (Agusti and Sánchez 2002). There are several fundamental problems confronted in present attempts to quantify viable organisms to evaluate ballast water treatment efficiency, outlined as follows.

A. Death of organisms by rapid concentration from large volumes

A major issue confounding the realistic representation of viable organism concentrations is that the rapid concentration of organisms from large volumes (which is a necessary prerequisite of enumeration) causes the death of many organisms across size classes. This concentration step must be accomplished quickly before organisms die– for example, within 6 hours for zooplankton. There is a fundamental disconnect in these requirements: It is difficult if not impossible to rapidly concentrate microflora and microfauna from very large volumes (hundreds of liters) by available filtration or centrifugation techniques without killing many of the organisms (e.g. Turner 1978, Cangelosi et al. 2007). Thus, even if at the time of counting viable organisms can be distinguished from dead organisms, what cannot be known is what proportion of the dead organisms were actually alive at the time of sampling.

B. Organism viability difficult to determine

Organism viability is not easily detected by a single morphological, physiological, or genetic parameter, making it advantageous to use more than one approach (Brussaard et al. 2001). However, the procedures used are specific to some taxonomic groups (e.g., vital stains), have varying degrees of uncertainty in categorizing live versus dead, and even the recommended procedures have practical limitations because of time constraints. For example, the ETV (U.S. EPA 2010) defines dead zooplankton operationally as individuals that do not visibly move during an observation time of at least ten seconds. Since live zooplankton may not move over that short period, death is verified by gently touching the organism with the point of a fine dissecting needle to elicit movement. However, the ETV acknowledges that if every apparently dead zooplankter in a concentrated subsample was probed and monitored for at least 10 seconds, analysis of the sample could be extended enough to increase the potential for sample bias due to death of some proportion of individuals that had survived the sampling and concentration procedures.

Finally, viruses also pose especially difficult challenges in determining viability, which have been little studied. Waterborne illnesses can involve a wide array of viruses; for example, enteric viruses, alone, that can be transmitted by water include poliovirus, coxsackievirus, echovirus, human caliciviruses such as noroviruses and sapoviruses, rotaviruses, hepatitis A virus, and adenoviruses (Howard et al. 2006). Reliable techniques for detection of infective viruses have only recently begun to become available even for determining the safety of potable freshwater supplies. Until very recently, potable water supplies have been evaluated using "surrogate bacteria" that are not accurate surrogates for viruses (Cromeans et al. 2005), or by standard techniques for *in vitro* cultivation in cell cultures that are affected by the same problems confronted for detection of viable bacteria – they are expensive, time-consuming, labor-intensive, and can easily miss various groups of infectious viruses (Fout et al. 1996).

C. Special challenges of resistant or nonculturable stages in attempts to assess viability

Resting stages (e.g., cysts) of some bacteria, phytoplankton, protists, zooplankton and metazoans are particularly resistant to motility, staining, and any other tests. For example, the protist size class (10 to < 50 µm) includes many species (microalgae, heterotrophic protists, metazoans) that form dormant cells or resting stages, or cysts (Matsuoka and Fukuyo 2000, Marrett and Zonneveld 2003). For example, cysts from potentially toxic dinoflagellates are commonly found in ballast waters and sediments (Hallegraeff and Bolch 1992). These cysts have been used as model indicator organisms to assess ballast water treatment efficiency (Anderson et al. 2004, Stevens et al. 2004), based on the premise that treatments which can eliminate the cysts likely also eliminate other, less resistant organisms (Bolch and Hallegraeff 1993, Hallegraeff et al. 1997).

Unfortunately, the resistant outer coverings of dormant cells such as protist cysts limit the utility of most vital stains and also can require application of multiple stains. Because resistant cells often have a low metabolic state and thick, multi-layered walls that are impermeable to many stains (Romano et al. 1996, Kokinos et al. 1998), their viability can be difficult to assess without culture analyses that may require weeks to months (Montresor et al. 2003, U.S. EPA 2010). As the ETV (pp.46-47) states, “At present, no rapid, reliable method to determine cysts’ viability is in widespread use, and the FDA-CMFDA method has yielded variable results with dinoflagellates and cyst-like objects.” The ETV recommends use of this method as a “place holder” until more effective methods become available.

Likewise bacteria populations, including human pathogens, also often contain cells that are alive but nonculturable. The effectiveness of ballast water treatment in removing viable bacteria is commonly evaluated by using multiple bacterial media in combination with taxon-specific molecular techniques (MERC 2009c, U.S. EPA 2010 and references therein). Colonies are monitored and quantified after ~1 to 5 days, depending upon the organism and its growth. These methods enable detection and quantification of viable, culturable cells. However, it has been repeatedly demonstrated that bacterial consortia across aquatic ecosystems commonly have a substantial proportion of cells which are active (viable) but nonculturable (Oliver 1993, Barcina et al. 1997 and references therein). These cells obviously would be overlooked in culturing techniques, a problem that would result in failure to detect viable cells of bacterial pathogens in treated ballast water. Under some conditions, the nonculturable organisms can regain activity and virulence (Barcina et al. 1997 and references therein).

D. Biased counts due to live, motile species changing their location in counting chambers

At the other extreme from resting stages are living organisms that are difficult to enumerate because they are highly mobile. Organisms are typically enumerated in counting chambers, based upon an underlying premise that the cells do not change their location in the chamber. However, many protists move rapidly by means of flagella or other structures. Because they do not maintain their position in a counting chamber, as live cells they could be counted multiple times. Moreover, their sudden movement can disrupt the locations of other cells in the chamber, mixing cells that may have been counted with other that have not yet. For these reasons, reliance on live counts can easily yield unreliable data.

E. Conclusion: indirect metrics for enumeration of viable cells should be added to standard protocols

Consideration of the above points – death during concentration of organisms, lack of reliable procedures to assess viability (especially for resting stages of many taxa), movement of live organisms in counting chambers that can result in serious quantification errors– leads the SAB to recommend that alternative approaches, including indirect metrics of the concentrationof viable organisms, be tested and added to standard protocols. These more inherent limitations add weight to the more practical considerations in section II above: the practical and inherent limitations converge as an argument for the greater development, testing, and implementation of indirect metrics of the concentration of viable organisms, including both surrogate species and surrogate parameters.

In addition to the indirect metrics reviewed in section II (e.g., vital stains, presence or abundance of taxon-specific DNA or RNA, algal pigments, adenylates, electron accepter colometric compounds), we add here an argument for using enumeration of preserved organisms as a surrogate for viable organisms. The use of preservation would also be compatible with the use of some (e.g., DNA, RNA) but not all (e.g., vital stains) other indirect metrics. The use of preserved concentrated organisms is commonly used in characterizations of microflora and microfauna assemblages in the peer-reviewed, published literature. It is based on the fact that protists and zooplankton deteriorate quickly once dead (within minutes to hours; e.g. Wetzel 2001, Johnson and Allen 2005). Thus "fast-kill" preservatives are used that cause death before distortion can occur; it is typically assumed that whole organisms with intact cellular contents were viable when collected. Obviously dead organisms are omitted from the count; for example, dead diatom cells are identified from the presence of empty silicon valves (cell walls (Knoechel and Kalff 1978). As shortcomings to this approach, dying organisms that still contain apparently intact cellular contents would be included in the "viable" estimate; and, as for counts based on unpreserved material, it is difficult to assess whether some resistant structures such as thick, opaque cysts contain organisms with intact cell contents. Because of practical and environmental health/safety constraints, neither approach avoids the problem of likely-major losses of viable organisms that occur during rapid concentration of large sample volumes.

Rigorous tests thus far are lacking to compare the "viable counts" and other indirect metrics to standard current practices in testing ballast water treatment technologies. Adding parallel implementation of indirect metrics to tests currently underway in testing facilities from different geographic regions could rapidly yield comparisons on which decisions for future testing could be made. Very likely, a combination of approaches will prove to be the most advantageous in estimating the concentration of viable organisms of different taxonomic groups.

IV. Approaches for Compliance/Enforcement of Ballast Water Regulations and Potential Application to Technology Testing

The US EPA has extensive experience in effective compliance and enforcement of discharge regulations. However, given the nature of ship ballast water discharge, new approaches will likely be needed. Both initial testing of treatment systems (sections II and III above) and methods currently available for potential compliance and enforcement monitoring are complex, slow and expensive. Statistical (see Section 1, this report) and logistical limitations related to collection of appropriate sample volumes and detection/quantification of live organisms in practice, mean that it may often be impossible to directly assess whether a vessel can meet all the numerical standards for viable organisms (King and Tamburri, 2010). No information was provided to the committee on whether protocols and systems for compliance monitoring (whether voluntary by ship operator or legally required) and enforcement were being considered alongside the development and testing of treatment systems. The committee feels that it is essential that these be developed in concert with treatment testing to avoid a situation where the creation of enforceable policy or rules is difficult or impossible.

The practical and inherent limitations suffered by the full protocols for certification testing of ballast water treatment systems (see section II and III above) have even greater force in the context of routine inspections (either self-inspections or regulatory inspections) (King and Tamburri 2010). They are simply not possible to use in the compliance and enforcement context. If alternative protocols that are practical for inspections are not developed, then neither self-compliance efforts nor regulatory enforcement will be possible once a system is installed on a ship. For example, treatment system malfunctions are inevitable. If some types of mechanical failure are not obvious to the operator or inspector, release of organisms may reach and maintain non-compliant levels for long periods of time with no detection of the malfunction, no penalty, and therefore no incentive to detect and fix the system. Unenforceable rules are bound to fail to meet the goal of reducing invasions. **Therefore, the SAB recommends that EPA develop a phased approach that includes metrics appropriate for compliance monitoring and enforcement before ballast water treatment standards or rules are adopted.**

A potential solution is the use of phased compliance reporting, inspections, and monitoring approach, described below, which involves a series of steps that increase the likelihood of detecting non-compliance but also increase in cost and logistic challenges (King and Tamburri 2010).

(1) *Reporting* – Vessel owner or ship master submits reports on the type of certified treatment system onboard and documentation demonstrating appropriate use and maintenance.

(2) *Inspections* – Enforcement official boards vessel and inspects the certified treatment systems to verify use and appropriate operations and maintenance.

(3) *Measures of system performance* – Indirect or indicative water quality measures are collected autonomously, or by inspectors, that demonstrate appropriate treatment conditions have been achieved (e.g. total residual oxidant [TRO] and/or oxidation reduction potential [ORP] sensors for chlorine and ozone treatments; dissolved oxygen and/or pH sensors for deoxygenation treatments; and radiometers or measures of power output + water transmittance for UV treatments). These types of instruments are available commercially, in wide use in oceanography and industrial applications, and can be adapted for ballast water.

(4) *Indirect measures of non-compliance* – Indirect or indicative measures of abundances of live organisms are collected autonomously, or by inspectors, for indications of clear non-compliance (e.g., ATP kits, in situ Chlorophyll fluorometers, vital stains + flow cytometry, particle counting and imaging systems, and molecular and genomic probes). Some of these approaches are used in treatment system testing (and other applications), others are still in development, andall will require rigorous calibration to direct measures of live organisms enumeration.

(5) *Measures of discharge standard* – Direct measures of concentration of live organisms in the various regulated categories are made by specially trained

technicians, with statistically appropriate sampling, and validated analyses and methodologies.

Protocols assessing indirect measures (particularly biological parameters such as chlorophyll, DNA, ATP) for concentration standards should be further developed for quick, easy, and defensible shipboard compliance monitoring.(These indirect measures are discussed in sections II and III above.) If sufficient foundation of rigorous studies demonstrate the relationship between indirect variables and the numerical standards for living organisms (specified in policy) then such surrogates could be used not only in future compliance and enforcement testing but also in initial testing of technology systems as suggested in sections II and III above.

V. Approaches Other Than Ballast Water Treatment

A. Introduction

Several approaches other than the treatment of ballast water could help to reduce the risk of biological invasions from ballast water discharges, and contribute to the achievability of discharge standards and permit requirements. While these approaches are often recommended, including by IMO, they are not often required or incentivized in practice. These approaches include ballasting practices to reduce the uptake of organisms, ballast water exchange to reduce the concentration of exotic organisms, reductions in the volume of ballast water discharged in U.S. waters, and management of the rate, pattern or location of ballast water discharge to reduce the risk of establishment. Although the committee’s charge questions focused on shipboard treatment, we consider these other approaches because, when used in combination with shipboard treatment, they appear to be capable of achieving a greater level of risk reduction than shipboard treatment alone.

B. Managing Ballast Uptake

Several studies have recommended various ballasting practices—sometimes referred to as ballast micro-management (Carlton et al. 1995; Oemke 1999; Dames and Moore 1998, 1999; Cohen and Foster 2000), shipboard management measures (Gauthier and Steel 1996), or precautionary management measures (Rigby and Taylor 2001a,b) – to reduce the number of organisms, or the number of harmful or potentially harmful organisms (such as bloom-forming algae and human pathogens found in sewage), that are taken up with ballast water (Table V.B-1). It is suggested that this can be accomplished by managing the time, place and depth of ballasting. Some of these measures have been included in laws, regulations or guidelines, including International Maritime Organization guidelines and the USCG rules implementing the National Invasive Species Act (Table V.B-2).[2] Although some of these regulations or guidelines have been in effect for nearly

20 years, there appear to be no data at all on levels of compliance and no studies of the effectiveness of any of these measures in reducing the uptake of organisms.

While there may be reasons for skepticism regarding the effectiveness or feasibility of several of these measures (AQIS 1993b; Cohen 1998; Dames and Moore 1998, 1999; Cohen and Foster 2000; Rigby and Taylor 2001b), some could be helpful in meeting stringent standards if vessels had sufficient incentive to implement them. The effectiveness of alternative ballasting (e.g. locations low in harmful organisms) and deballasting practices (e.g. locations and practices to reduce concentrating propagules) should be quantified. As an example of the former, research has shown that taking up ballast water in areas affected by toxic dinoflagellate blooms, followed by deballasting in another location, can result in distribution of those blooms to previously unaffected areas (Hallegraeff and Bolch 1991). Clearly, such action should be avoided as routine practice, and can also help to meet BWTS standards.

The value of such practices could be evaluated with models using currently available data on organism distributions or by experimental approaches. To the extent these practices would reduce the uptake of organisms, they could be used by vessels to help them meet any discharge standards that might be adopted. From the perspective of overcoming technical limitations on the feasibility of meeting different discharge standards, such practices would allow the adoption of -- and vessel compliance with -- more stringent standards than would otherwise be achievable. Thus, there are valid reasons for the US EPA to consider the potential for employing these practices in combination with ballast water treatment to further reduce the risk of releasing exotic organisms in U.S. waters.

C. Reducing Invasion Risk from Ballast Discharges

Mid-ocean ballast water exchange has the potential, in combination with the other approaches discussed here, to further reduce the concentration of exotic organisms (though not necessarily reduce the concentration of all organisms) in ballast discharges. There is general agreement that when properly done ballast water exchange can reduce the concentration of initially-loaded organisms by about an order of magnitude on average (Minton et al. 2005).

Invasion risk is positively related to the total number of propagules released in a given time and place. Thus, risk is positively related to the concentration of propagules times the volume of the discharge. Even if the concentration of propagules is unmanaged, reducing discharge volumes will reduce invasion risk in ways that are predictable across taxa (Drake et al. 2005).

Technologies and practices to reduce the volume of ballast water discharged in US waters could include:

- operational adjustments;
- systems that allow shifting of ballast water between tanks;
- larger, wider vessels that require less ballast water per unit of cargo; and
- the potential development of ballastless vessels.

The second and third bullets describe changes in ship design that are already occurring and are driven by economic factors. Ballast regulations that address not only the *concentration* of organisms in ballast discharges but also the *volume* of ballast water discharged could further encourage these developments.

Independent of practices of ballast water uptake (previous section) and total volume of a given discharge, operational adjustments that modify the temporal and spatial patterns of ballast water discharge may also reduce the probability that discharged propagules will found a self-sustaining population (Drake et al. 2005). At least for sexually reproducing populations of planktonic species, for a given concentration of a given species in ballast discharge, the greater the volume discharged in a given time at a given location, the greater the probability of population establishment. If a total discharge volume for a given port of call can be broken up in space or time, invasion risk will be lowered. Thus, if a given discharge volume can be spread over space (e.g., as a vessel approaches harbor), be discontinuous in time (with scheduled breaks in discharge), or be discharged in a mixing environment (to dilute the concentration of propagules), the risk of invasion will be lowered (Drake et al. 2005).

For the same reasons, infrastructure modifications within ports that increase the rate and/or magnitude of dilution of discharged propagules would also decrease the risk of population establishment by discharged propagules. If discharges could be made in or piped to locations of greatest mixing within the harbor (e.g., closer to the tidal channels instead of in partially enclosed ship slips), then the rate of diffusion would be more likely to overcome the rate of reproduction. For example, low velocity, low energy propellers, oloid mixers, or other mixing methods are routinely used in sewage treatment plants, industrial applications, and lakes. Such devices could be used in ports to increase the severity of Allee effects and other population hurdles faced by newly discharged propagules to minimize the probability of population establishment.

VI. Combined Approaches and Voyage-based Risk Assessment

A. Combined Approaches

It may be possible to meet more stringent discharge standards, or otherwise reduce the risk of invasions from ballast water discharges, by combining the approaches discussed in previous sections (sections II and III, technologies and procedures involved with ballast uptake and discharge) with either shipboard or onshore treatment. Each step from ballasting to deballasting, including the choice of procedures and the choice of technologies, contributes to the probability of an invasion occurring (see separate section on risk assessment and HACCP). Recognizing and better quantifying the probability associated with each step could better target management efforts and achieve reductions in the overall probability of invasion at lower cost than relying on only one technology.

B. V oyage-based Risk Assessment to Prioritize Use of Treatment Technologies, Ballasting and Deballasting Practices, Monitoring Efforts, and Enforcement

Most current ballast water treatment technologies (see other sections of this report), and the current and proposed policies that motivated them, are built with a one-size-fits-all approach and designed to be adopted by hundreds of ships at some (possibly distant) future time. There are defensible reasons for this one-size-fits-all approach, but as we argued in the previous subsection, additional reasons exist to consider more flexible and combination approaches. This is especially true in the face of tight budgets and the constant need to prioritize spending on the most cost effective strategies to reduce invasion risk. Furthermore, invasion risk clearly differs among ships, voyages, and ports in ways that are predictable, and that could provide a basis for guiding the deployment of combinations of technologies and practices now and in the future (Keller et al. 2010). For example, to most cost effectively minimize invasion risk while ballast water treatment systems are being phased in, the highest risk ships that conduct the highest risk voyages should be retrofitted first. Likewise, ship-voyage specific risk assessments could guide the schedules for compliance monitoring of the operation and condition of installed water treatment systems.

VI. Onshore Treatment

Onshore treatment involves either treatment facilities built on land or treatment facilities installed on a port-based treatment ship, which will be referred to as “on-land” and “treatment ship” approaches, respectively. Some reports have taken onshore treatment to mean the treatment of ballast water in existing wastewater treatment plants. This is considered here as a special case of on-land treatment. Currently, some oil-contaminated ballast water is discharged to on-land facilities designed to separate hydrocarbons from the water. Some studies have considered modifying these facilities to remove or kill organisms in ballast water, and this is also treated here as a special case of on-land treatment. Other reports have considered using existing water or wastewater treatment plants as sources of clean ballast water that could be loaded on ships and later discharged without further treatment, or onshore facilities that would pump hot water into a ship’s partially empty ballast tank to kill organisms in it (=external source treatment, Aquatic Sciences 1996). These approaches are not considered to be onshore treatment in this report. The discussion and assessment of onshore treatment in this report refers to treatment in onshore facilities that are built specifically and solely to receive and treat ships’ ballast water in order to remove or kill organisms, except where explicit reference is made to treatment in existing on-land treatment facilities.

The discussion includes a review of the literature on efficacy of onshore treatment, a comparison of onshore treatment relative to shipboard treatment, an analysis of costs relative to shipboard treatment, an assessment of the capability of onshore treatment to meet various levels of discharge standard, and a summary of conclusions and recommendations. Further details on each of these topics can be found in the appendices.

A. Efficacy of Onshore Treatment

Onshore treatment has been briefly commented on in several studies, but significantly analyzed in only a few (Table A1-1 in Appendix 1). Some studies concluded that onshore treatment is a technically feasible option either for the industry as a whole or for some part of the industry (NRC 1996; Oemke 1999; CAPA 2000; California SWRCB 2002; Brown and Caldwell 2007, 2008); none found it to be technically infeasible. A few concluded that cost or other factors could limit its use to part of the industry, but provided no data or analyses to support this (Victoria ENRC 1997; Dames & Moore 1998, 1999; Rigby & Taylor 2001a,b; California SLC 2009, 2010). The U.S. EPA and U.S. Coast Guard reports (EPA 2001, Albert et al. 2010, US Coast Guard 2008) that deal with ballast water management contain neither analyses nor significant discussions of onshore treatment. However, the potential for treating ballast discharges onshore has been repeatedly recognized in laws and regulations, and in international guidelines and treaty conventions (Appendix A1). Two studies provided conceptual designs and cost estimates for onshore treatment for specific regions. CAPA (2000), an EPA-funded study, developed designs and cost estimates for the state of California, and Brown and Caldwell (2007, 2008) did the same for the Port of Milwaukee. Recent studies by Glosten (2002) and Brown and Caldwell (2008) based their analyses on designs that allow ships to deballast completely during the time needed for cargo loading at berth.

B. Onshore Treatment Compared to Shipboard Treatment

Onshore ballast water treatment systems have been compared with shipboard treatment in various studies. Three studies compared the effectiveness of onshore and shipboard ballast water treatment. Pollutech (1992) ranked onshore treatment second in terms of effectiveness, feasibility, maintenance and operations, environmental acceptability, cost, safety and monitoring out of 24 ballast water management approaches for vessels entering the Great Lakes. Aquatic Sciences (1996) estimated the costs of using treatment ships to treat ballast water discharge in the Great Lakes, and concluded that onshore treatment approaches are technically feasible, "more practical and enforceable" than shipboard treatment, and "offer the best assurance of prevention of unwanted introductions." California SWRCB (2002) found onshore treatment to be the only approach to have acceptable performance in all three categories of effectiveness, safety, and environmental acceptability in a qualitative comparison with ten shipboard treatment alternatives. Several other published comparisons of onshore and shipboard treatment consist of lists or brief discussions of their relative merits without significant analysis. Descriptions of these comparisons are provided in Appendix 1.

The following points summarize the findings of studies comparing onshore and shipboard treatment. A more detailed discussion of these points can be found in Appendix 1.

1. Number of treatment plants and total treatment capacity

For shipboard treatment, a treatment plant is installed on each ship and treat ballast water either during uptake, discharge, or both (Table VI.B-1),[3] and must be large enough to accommodate the ship's maximum ballast pumping rate (ABS 2010). This is assumed to be equal to a ship's total ballast pump capacity, which is often in the 1,000-2,000 MT/h range and can be as high as 20,000 MT/h (Table A4-1 in Appendix 4). The total treatment capacity needed is equal to the sum of the ballast pump capacities of all the ships. One onshore treatment plant serves a number of ships, and because all ships do not arrive and discharge ballast water simultaneously, the treatment capacity needed is less than the sum of the maximum ballast discharge rates of all ships. However, some ballast water storage is usually included in an onshore plant and can be sized to reduce the needed treatment capacity to the average ballast water discharge rate (e.g., see AQIS 1993a; Ogilvie 1995; CAPA 2000; Brown and Caldwell 2007, 2008).

Table VI.B-1. Percentage of shipboard ballast water treatment systems that treat during ballast uptake, ballast discharge, or both. Treatment phase and commercial availability (through 2009) from Lloyd's Register 2010, Tables 5 & 6. Type approval (though February 2010) from ABS 2010, Table 7.

Treatment Phase	All treatment systems (n=41)	Commercially available systems (n=21)	Type-approved systems (n=10)
Uptake only	37%	48%	50%
Discharge only	7%	4%	0%
Both	51%	48%	50%
Uptake or discharge	95%	100%	100%

Table VI.B-2 compares the estimated number of individual treatment plants and the total treatment capacity that would be needed for onshore vs. shipboard treatment in the Port of

[3] Physical separation processes (filtration, electro-mechanical separation or hydrocyclones) all produce an untreated waste stream (backwash from filters or underflow from hydrocyclones), which essentially requires that these processes be conducted during ballast uptake so this untreated water can be discharged back to the source waters (Cohen & Foster 2000; California SLC 2010; Lloyd's Register 2010). UV is generally applied immmediately after this initial particle-removal process, because it is less effective if particles are present in the water, and in some treatment systems is also applied, without further filtration/particle removal, during discharge (ABS 2010). Biocides are generally injected during uptake, to promote mixing and maximize contact time. Chlorine is generally injected (or created by electro-chlorination) immediately after particle removal both to enhance its effectiveness and to maximize contact time, and chlorine neutralization (which occurs nearly instantaneously) is then conducted during discharge. In all of these cases, which cover most of the treatment processes being used to address ballast water, the system must be sized to treat the maximum ballast flow rate on uptake or discharge. Deoxygenation appears to be the only treatment approach that is, in some systems, applied only during the voyage and not during either uptake or discharge (Lloyd's Register 2010; ABS 2010).

Milwaukee, Australia, California and the United States, over a 20-year (Milwaukee) or 30-year (other sites) project life. The onshore plants and capacities are based on adjusted estimates from the available studies (Brown and Caldwell 2008, AQIS 1993a and CAPA 2000, respectively); these estimates are explained in Appendix 4.

Table VI.B-2. Treatment plant and capacity estimates for the Port of Milwaukee, Australia, California and the United States. Assumptions and methods are described in Appendix 4.

	Number of Treatment Plants		Total Capacity of Treatment Plants (MT/h)	
Site	**Onshore**	**Shipboard**	**Onshore**	**Shipboard**
Milwaukee	1	19	230	22,800
Australia	23	2,160	34,940	1,188,000
California	16	13,115	1,814	18,883,140
United States	314	83,200	35,549	119,475,200

Based on these estimates, the number of plants needed for shipboard treatment over the project period is from 19 times to >800 times the number needed for onshore treatment. The treatment capacity needed for shipboard treatment is from >30 to >10,000 times the capacity needed for onshore treatment.

2. Constraints on treatment

Major constraints on shipboard treatment have been discussed earlier in this document (cite Section) and include limited space (Pollutech 1992; AQIS 1993a; Aquatic Sciences 1996; NRC 1996; Cohen 1998; California SLC 2010; Albert & Everett 2010), limited power availability (NRC 1996; Cohen 1998; California SLC 2010), limited treatment time (NRC 1996; Oemke 1999) and an unstable platform (AQIS 1993a; Cohen 1998; Reeves 1999). These constraints are largely absent in onshore systems.

3. Treatment methods available

Any treatment method used on ships can be used onshore; however, there are treatment methods available for use onshore that cannot practically be used on ships because of space, stability, time or safety constraints. These include such common and relatively inexpensive water or wastewater treatment processes as settling tanks, flotation processes and granular filtration[4]

[4] Sometimes called media filtration or deep media filtration.

(AQIS 1993a; Gauthier & Steel 1996; NRC 1996; Victoria ENRC 1997; Cohen 1998; Reeves 1999; Cohen & Foster 2000; California SWRCB 2002) and the use of chlorine gas for disinfection (Cohen & Foster 2000), as well as microfiltration, ultrafiltration and reverse osmosis processes (AQIS 1993a; California SLC 2010). Settling tanks and flotation processes require a steady free surface and are feasible only in onshore applications (AQIS 1993a; Gauthier & Steel 1996; Cohen 1998; Reeves 1999). Granular filtration could in theory be employed shipboard in pressurized containers (AQIS 1993a), but space requirements make it impractical (Gauthier & Steel 1996; NRC 1996; Cohen 1998; Reeves 1999; Cohen & Foster 2000).

4. Plant operation by trained water/wastewater treatment personnel

Shipboard treatment plants will likely be operated and maintained by ships' regular crewmembers in addition to their existing duties (NRC 1996; California SLC 2010). Several researchers have noted that the quality of operation and maintenance will probably suffer (Pollutech 1992; AQIS 1993a; Aquatic Sciences 1996; Reeves 1998), or that operation of treatment systems by better trained personnel in onshore plants would result in superior performance (Cohen 1998; California SWRCB 2002; Brown & Caldwell 2007; California SLC 2010). Maintenance and repair work are also more likely to be done effectively, and needed replacement parts obtained more quickly, in onshore plants (AQIS 1993a; Aquatic Sciences 1996; Cohen 1998; Cohen & Foster 2000).

5. Safety

Shipboard treatment involves restricted working spaces and difficult and potentially hazardous working conditions at sea (AQIS 1993a; Cohen 1998; Cohen & Foster 2000), which increases the risk of accidents related to treatment processes or materials. For processes that involve the storage and use of biocides or other hazardous chemicals, there is greater risk of harm to personnel in shipboard than in onshore applications (AQIS 1993a; Carlton et al. 1995; Reeves 1998; Cohen 1998; Cohen & Foster 2000) and greater risk of accidental discharge to the environment (Pollutech 1992; AQIS 1993a; Carlton et al. 1995). In addition, because many processes cannot be used onboard ships (as discussed above), shipboard systems will likely rely on biocides to a greater extent than will onshore systems to achieve a given level of treatment.

6. Reliability

Operation and maintenance by trained wastewater treatment staff and safer, more predictable working conditions should produce more reliable and consistent performance. Reliability can be further improved by building redundancy into an onshore plant; this will often be impractical in a shipboard plant due to space constraints. Furthermore, bypassing a shipboard treatment plant designed to operate inline during ballasting, or failing to employ it effectively, at any point in the history of the treatment plant could compromise the quality of later discharges, since organisms (e.g., cysts or other resting stages) retained in large numbers in sediments at the bottom of ballast tanks could contaminate properly-treated ballast that is loaded later (AQIS 1993a; Reeves 1998).

7. Adaptability

Because of space restrictions on ships and structural cost factors that make treatment components a smaller part of the total cost of treatment in onshore applications, it is both physically and financially easier to retrofit, replace, or upgrade onshore than shipboard treatment systems. Brown and Caldwell (2008) note that onshore systems would "provide treatment flexibility, allowing additional treatment processes to be added or modified as regulations and treatment targets change"

8. Compliance monitoring and regulation

The effort of regulatory monitoring and enforcement needed to achieve a given level of compliance is expected to be much less for a relatively small number of onshore, domestic treatment plants compared to a much larger number of mobile, transient, sometimes foreign-owned[5] shipboard treatment plants, which are accessible only when in a U.S. port (AQIS 1993a; Ogilvie 1995; Aquatic Sciences 1996; Cohen 1998; Dames & Moore 1999; Oemke 1999; Cohen & Foster 2000; California SWRCB 2002; Brown and Caldwell 2007). Several studies noted the difficulty of monitoring shipboard treatment and the greater ease of monitoring and inspecting onshore treatment (AQIS 1993a; Cohen 1998; Dames & Moore 1999; Cohen & Foster 2000; California SWRCB 2002; California SLC 2010).

9. Overall Effectiveness

Many of the above advantages—the absence of the space, time and power constraints, the ability to use common and effective water and wastewater treatment processes, the operation and maintenance of treatment systems by trained personnel, and the greater ability to install extra capacity and redundancy—will tend to make onshore treatment more consistently effective at removing or killing organisms in ballast water. Other factors that make it possible to concatenate a larger and more effective set of treatment processes in onshore plants (Appendix 1), and the greater adaptability of onshore treatment also increase the potential effectiveness of onshore relative to shipboard treatment. Dames & Moore (1999) reported that onshore treatment provided

[5] Roughly 20% of the 40,000 cargo ships estimated to be subject to the EPA's Vessel General Permit are foreign-flagged (Albert & Everett 2010). What fraction are foreign-owned is not known.

"complete control of effectiveness," and Lee et al. (2010) stated that compliance with a zero discharge standard is feasible only with on-land treatment.

C. Concerns About Onshore Treatment

Eight issues of concern with onshore treatment have been identified in the literature and during our committee deliberations.

1. Ballast discharge before arrival to reduce time spent at berth

Several studies noted that some vessels, including bulk carriers, may discharge part of their ballast water before arriving at berth so they can complete discharge by the time the cargo is loaded (AQIS 1993a; Oemke 1999; Cohen & Foster 2000; CAPA 2000; Rigby & Taylor 2001a). For a bulk carrier "normal vessel operation may involve dumping up to 20% of ballast water in coastal waters as it approaches port" (AQIS 1993a). However, if the "rate at which the cargo is to be loaded is such that the ship's ballast pumps can discharge ballast at a comparable or higher rate, deballasting may be carried out entirely while alongside the berth" (AQIS 1993b). One potential solution is to outfit a ship's ballast water system with pipes and pumps that are large enough to allow the ship to unload ballast water as quickly as it loads cargo. The issue then becomes whether this is so expensive that the overall cost of treating ballast water onshore becomes untenable. Glosten (2002) and Brown and Caldwell (2007, 2008) developed cost estimates for retrofitting bulk carriers and other vessels to allow them to deballast at berth during the time they load cargo, and these estimates are used in the cost analysis below (§VI.D).

2. Ballast discharge to reduce draft before arriving at berth

Several studies also noted that a ship might discharge ballast water before arriving at berth to reduce draft in order to cross over a shallow bar or to enter a shallow channel (Cohen 1998; Dames & Moore 1998, 1999; Oemke 1999; CAPA 2000, Rigby & Taylor 2001a; California SWRCB; California SLC 2010). None of these studies provide data indicating whether this is a common circumstance. Several studies note the possibility of addressing this issue by offloading some ballast water to a barge before arriving at berth, a practice that some ships at some ports routinely do for liquid cargo (a process called lightering) (AQIS 1993a; Carlton et al. 1995; Dames & Moore 1999; CAPA 2000; Rigby & Taylor 2001a; Glosten 2002; California SWRCB 2002). Dames & Moore (1998) suggested that a treatment ship (that is a vessel with an installed treatment plant designed to receive *and treat* ballast water from cargo ships) could "service deep-drafted high-risk arrivals that need to deballast during approach to shallow berths at neap tide periods." Whether this would be generally feasible or cost-effective is unclear.

Another approach is for the shipping industry to adjust operationally, that is, to send cargo to a port on ships that can reach berth without having to partially deballast first. The industry makes this type of operational adjustment by taking into consideration the characteristics of the port and the channels that must be traversed when deciding which ship to send to which port carrying which cargo, and they have a great deal of expertise in selecting the most efficient, least cost option to do so. Adding the additional constraint of not being able to discharge ballast water before arriving at port would have some cost, but the industry is set up to make operational decisions to minimize this cost. The overall cost depends on how commonly this circumstance occurs and the cost of making these operational changes, and we could not find quantitative data to analyze this. However, one knowledgeable authority stated that ships today are sent to harbors that can accommodate them without having to reduce their draft, and that ships that shed ballast coming into a harbor nearly always do so in order to reduce deballasting time at berth (Captain Philip Jenkins pers. comm. to Fred Dobbs).

3. Delays

Several studies have noted the possibility of costly delays (Dames & Moore 1998, 1999; Cohen 1998; Oemke 1999; Cohen & Foster 2000; CAPA 2000) because of issues discussed in 1 and 2 above. Since delaying a ship is generally quite costly, the least cost option will in most cases be to outfit the ship with ballast pipes and pumps that are large enough to allow deballasting to occur as rapidly as cargo loading, and to ship cargo to ports on ships that can enter those ports without having to offload ballast or cargo or wait for higher tides.

4. Cost recovery

Some studies stated that cost recovery could be an issue (Dames & Moore 1998; Oemke 1999). Regional governments and ports will have to decide whether they want to pay for part or all of the cost of ballast water treatment, or whether ships will be charged a fee for having their ballast treated in an onshore plant.

5. Cost

This issue is discussed in Section VI. D below.

6. Invested effort

Parties have spent considerable time working on shipboard treatment systems, and the U.S. should not waste this effort by adopting discharge standards so stringent that shipboard treatment would be abandoned in favor of onshore approaches. In economic and business analysis this is described as a decision based on retrospective or sunk costs. Although hypotheses have been advanced to explain why individuals or institutions sometimes make decisions based on sunk costs, these decisions are considered to be irrational or maladaptive (e.g., Arkes & Blumer 1985; Keasey & Moon 2000)..

7. Timing

Some have argued that it will take longer to build onshore plants than to install shipboard plants, although this has not been documented. Barring site-specific difficulties that could occur, the expected time to complete design, permitting and construction of an onshore treatment plant is about 30 months for plants larger than 10 mgd (≈1580 MT/h) (Robert Bastian, US EPA Office of Water, pers. comm. in email to Dr. Charles Haas, 12/06/10). Virtually all the onshore plants needed in the U.S. would be smaller than 10 mgd[6] and should take less time to complete. Shipboard treatment systems can presumably be installed on new vessels during construction without significantly increasing construction time. However, for the 40,000 existing cargo ships (and 29,000 other vessels) that are expected to be subject to the VGP, either installing a shipboard plant or modifying its ballast system so it can discharge ballast water to an onshore facility would require the vessel to be out of service either in drydock or at wharfside where this work could be done. This occurs infrequently, with hull inspections with or without drydocking typically occurring every 2.5-5 years, although the time for these activities may not always be long enough to allow treatment system installation or ballast system modification (Captain Phil Jenkins, pers. comm. to Dr. Fred Dobbs)[7]. The time to complete the construction of either shipboard or onshore treatment is thus likely to be about the same.

An additional factor is the time needed to develop an effective monitoring and enforcement program. As discussed earlier, a larger and more costly program would be needed to monitor and enforce shipboard treatment than onshore treatment. Depending on how rapidly the EPA moved to develop a monitoring and enforcement program, this could affect the overall time to implementation.

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[6] CAPA (2000) estimated that onshore ballast water treatment in California would require two 1 mgd plants and eight 0.1-0.2 mgd plants. When these estimates are adjusted upward with more recent and complete ballast water discharge data, the largest plant needed is still only 3.7 mgd, and 80% are less than 0.6 mgd. Nationwide ballast water discharge data (Miller et al. 2007) are compiled by regions known as Captain of the Port Zones (COTPZs), which may cover more than one port. These data, after being increased to adjust for reporting rates, show only five COTPZs in the U.S. with average ballast water discharge rates at or above 10 mgd: Houston-Galveston (22 mgd), Prince William Sound (20 mgd), Duluth (16 mgd), New Orleans (14 mgd) and Saulte St. Marie (10 mgd). It appears that at most a handful of onshore ballast water treatment plants will be needed that are larger than 10 mgd.

[7] The implementation schedule in the IMO convention (which phases in the D2 discharge standards over an 8 year period) was designed at least in part to address the necessity of installing shipboard plants during infrequent out-of-service periods.

8. International issues

Some have argued that the U.S. should not base its discharge standards on the efficacy of onshore plants because adopting standards that can be met with shipboard treatment would allow ships to install shipboard systems, which could indirectly benefit other countries that are unlikely to build the facilities needed to treat ballast water onshore. _For this to occur, the benefitting country would have to (1) be unable or unwilling to implement either ship-based or onshore treatment if the U.S. adopted strong standards that required onshore treatment[8], and (2) be willing and able to adopt discharge requirements and a compliance monitoring and enforcement regime sufficient so that installed treatment systems would be used on voyages to the benefitting country if the U.S. adopted standards that could be met with shipboard treatment.

U.S. adoption and implementation of stronger standards requiring onshore treatment would better protect U.S. waters from invasions, thereby benefiting other countries by preventing U.S. waters from serving as "stepping stones" from which invasions may reach other countries. In addition, if the U.S. adopted stronger standards and onshore treatment, this could encourage other countries to do so, which would have further global benefits.

D. Cost of Onshore vs. Shipboard Treatment

As discussed above, onshore treatment of ship's ballast water is technically feasible; the question is whether this be done at a total cost that renders it impractical. Several studies mention one or another element of the cost of onshore treatment, or mention costs generally, as a disadvantage of onshore treatment (Cohen 1998; Dames & Moore 1998: "expensive connection problems"; Dames & Moore 1999: "high costs of construction"; Rigby & Taylor 2001b: "high cost of the installation"; California SLC 2010: costs "may be prohibitive...the acquisition of land for facility construction...would be...costly"). In contrast, AQIS (1993a) found onshore treatment to be cheaper than shipboard treatment in both single-port and nation-wide scenarios in Australia, concluding that onshore treatment facilities "are more economic and effective than numerous ship-board plants." Cost estimates compiled by the U.S. Coast Guard (2002) also showed onshore treatment to be generally less expensive on a per metric ton basis than shipboard? treatment. Several studies have estimated the costs of modifying ships so they can discharge ballast water to onshore facilities; these costs vary considerably with ship type and size (Table A1-7 and Figure A1-2 in Appendix 1).

Dames & Moore (1999) states that onshore treatment is "an expensive option for ports with a low incidence of high-risk arrivals." Constructing and operating a treatment plant in ports that

[8] We note that onshore treatment plants have the potential to become profit centers for receiving ports or countries—that is, onshore plants could charge ships fees that would pay for the costs of construction and operation *and* turn a profit (Cohen & Foster 2000)—thus perhaps making them somewhat more likely to be constructed in other countries if the U.S. leads the way.

receive little ballast water will result in high costs per MT of ballast water treated at that plant. To address this concern, AQIS (1993a) proposed deploying barges to receive ballast discharges in smaller ports, which would periodically transport the collected ballast water to treatment plants located in the larger ports. For a port receiving <500 gallons/day, CAPA (2000) proposed an on-land pipe system and storage tank to receive and store ballast water, which would periodically be barged to treatment plants a short distance away. At small ports the question of whether to build an onshore treatment plant, or to build an onshore storage tank with periodic transport to larger ports, or to deploy a barge to collect and transport ballast water, will be decided based on the relative costs of each.

It is beyond the scope of this committee's work to determine what the maximum acceptable total cost of treating the nation's ballast discharges might be. A far simpler question is: How does the total cost of treating ballast water onshore compare to the total cost of treating ballast water on ships? If shipboard treatment is considered economically feasible[9], and onshore treatment is not significantly more costly, then onshore treatment could also be economically feasible. In the following discussion we compare the total estimated costs of onshore or shipboard treatment needed to deal with ballast water discharged into California waters, and then extend those estimates to all U.S. waters. The California estimate is based on the most relevant and complete estimate of onshore treatment costs available, the CAPA (2000) study, augmented by other available sources of information to estimate costs that were not included in the CAPA estimate[10]. For the U.S., onshore costs are estimated by multiplying the California onshore cost by the ratio of total U.S. ballast water discharge to discharge into California waters[11].

[9] We don't know whether any government body has determined that shipboard treatment of ballast water is economically feasible, and we are not making that determination here. We only note that shipboard ballast water treatment systems have been installed and are operating on some ships (Lloyd's Register 2010); that the interest and activities of the shipping industry, equipment manufacturers and investors in shipboard treatment systems suggest that they believe that it is economically feasible; and that the IMO's ballast water convention, the ratification of that convention by various port states, the laws and regulations adoped by various U.S. states, the regulations proposed by the U.S. Coast Guard, and the convening of this committee and the charge questions provided to it by the Office of Water suggest that those entities also believe that shipboard treatment is economically feasible.

[10] Shipboard treatment costs for California are based on the estimated number of distinct ships arriving in California ports and the ballast pump capacities of those ships, derived from data in Ballast Water Reporting Forms submitted by ships arriving in California since January 1, 2000 (California SLC 2010), and on recently published estimates of shipboard treatment system costs in Lloyd's Register (2010).

[11] These figures are derived from data in Ballast Water Reporting Forms submitted by ships arriving in U.S. ports in 2004-2005, which is the most recently compiled data available (Miller et al. 2007). Shipboard treatment costs are based on the number of distinct ships estimated to be subject to the VGP (Albert & Everett 2010) and the recent estimates of shipboard treatment costs (Lloyd's Register 2010). As no data are available on the ballast pump capacities of the ships subject to the VGP (Ryan Albert, pers. comm. in SAB public conference call 10/26/10), we applied the ballast pump capacity figures for ships arriving in California (California SLC 2010).

Costs were adjusted to current (June 1, 2010) U.S. dollars and annualized costs were calculated as described in Appendix 2. Because of differences in the estimated working lifetimes of different project elements (Appendix 2), annualized costs were used for the comparisons. Sensitivity analyses were conducted by varying the inputs over a range of estimates to test the robustness of the results (Appendix 5-to be completed).

1. Onshore treatment cost estimate for California

The basic onshore cost estimate is a modified version of the CAPA (2000) estimate, which includes the following elements: piping from berths to plants; storage tanks; a treatment system consisting of coagulation, flocculation, filtration and UV disinfection, plus solids thickening, dewatering and disposal; and discharge through an outfall pipeline (detailed in Appendix 1). The treatment system costs include both capital costs and O&M (operations and maintenance) costs. For the other elements only capital costs were estimated, as O&M costs were assumed to be minor. We modified the CAPA (2000) estimate as follows:

- CAPA (2000) used an inappropriate method that underestimated annualized costs. We estimated annualized costs as described in Appendix 2.
- CAPA (2000)'s estimated costs were adjusted to June 1, 2010 dollars as described in Appendix 2 (the adjusted estimates by port are shown in Table A1-4 in Appendix 1).
- We estimated total ballast water discharge in California based on the most recent data as described in Appendix 4, and adjusted the CAPA (2000) estimated costs upward to correspond to our estimate of total ballast discharge.
- Land costs were not included in the CAPA (2000) estimate. We estimated these from the sale prices for vacant land near California's ports advertised on the Internet, with the size of the properties needed based on estimated treatment plant footprints and the storage tank footprints from CAPA (2000), adjusted to larger storage and treatment capacity requirements based on our larger estimate for total ballast water discharge.
- The costs of retrofitting existing ships and constructing new ships with ballast water pipes and pumps designed to allow ships to discharge ballast water to onshore facilities were not included in the CAPA (2000) estimate. We estimated these costs based on the literature on ship retrofit costs (§VI.A and Appendix 1)[12], and the number of ships arriving at California ports, derived in Appendix 4 from California State Lands Commission data.

These successive adjustments are shown in Table VI.D-1. The details of these calculations are provided in Appendix 5 (to be completed).

Table VI.D-1. Modified cost estimates for onshore treatment in California. See text for explanation. Estimates are rounded to the nearest $1,000.

[12] We used the cost estimates in Glosten (2002) and Brown and Caldwell (2008), which were based on engineering designs with large enough pipes and pumps to enable ships to complete deballasting at berth during the time it takes to load cargo, thereby eliminating the economic basis for the practice of partially deballasting en route to berth.

Capital Costs						
Ship Retrofit/ Modification	**Pipes**	**Storage Tanks**	**Treatment Plants**	**Outfalls**	**Treatment-Annual O&M**	**Total Annualized Costs**
Cost estimates from CAPA (2000):						
—	117,110,000	60,755,000	17,941,000	1,100,000	1,608,000	8,171,000
...with costs annualized per Appendix 2:						
—	117,110,000	60,755,000	17,941,000	1,100,000	1,608,000	14,417,000
...adjusted to June 1, 2010 dollars per Appendix 2:						
—	146,950,000	76,235,000	22,513,000	1,380,000	2,018,000	18,091,000
...adjusted to our updated estimate of total ballast water discharge:						
—	475,814,000	282,764,000	40,690,000	5,112,000	7,485,000	59,812,000
...with land cost and ship retrofit/modification costs included:						
1,763,427,000	475,814,000	377,358,000	57,240,000	5,120,000	7,485,000	181,755,000

2. Onshore treatment cost estimate for the United States

The cost of onshore treatment for ballast water discharged into U.S. waters was estimated by multiplying the Californai cost estimate by the ratio between the annual ballast discharge in the two regions. The cost for ship retrofit/modification was estimated as for California. The resulting estimates are shown in Table VI.E-2. Details are in Appendix 5 (to be completed).

Table VI.E-2. Cost estimates for onshore treatment in the United States. See text for explanation. Estimates are rounded to nearest $1,000.

Capital Costs						
Ship Retrofit/ Modification	**Pipes**	**Storage Tanks**	**Treatment Plants**	**Outfalls**	**Treatment-Annual O&M**	**Total Annualized Costs**
10,755,934,000	9,320,836,000	7,392,162,000	1,121,282,000	100,289,000	146,632,000	2,012,991,000

3. Shipboard treatment cost estimates and comparison

Shipboard treatment cost estimates for both California and the United States were based on the numbers of ships expected to be subject to ballast water regulations (Appendix 4) and the average costs of installing treatment systems on those ships. For both regions the average maximum ballast pumping rate for ships was assumed to be 1,436 MT/h, which is the California average (Appendix 4). The estimated average cost of an installed shipboard treatment system was based on the eight treatment systems for which type approval is reported as received or pending in Lloyd's Register (2010) or ABS (2010), and for which capital cost data were provided for both 200 and 2,000 MT/h treatment plants (Table 5 in Lloyd's Register 2010). The capital cost for a 1,436 MT/h plant was interpolated for each of these eight systems, and the average of these was used as the estimated average cost. The results, as total annualized costs, are $462,468,000 for shipboard treatment in California (roughly 2.5 times the annualized onshore costs) and $2,939,175,000 for the United States (about 50% greater than the onshore costs). The sensitivity tests in Appendix 5 illustrate that the general results—that the total costs of onshore treatment are of the same order as or somewhat less than the total costs of shipboard treatment—are robust.

In onshore treatment, the treatment cost (capital plus O&M) is a modest fraction of the total cost: about 6% of the total in California, and about 11% of the total in the United States. Ship retrofitting, onshore pipe systems and storage tanks are each a larger fraction of the total cost. In shipboard treatment, however, all of the cost is treatment cost. This means that if an additional amount is spent to improve the effectiveness of the treatment process, for example by concatenating additional treatment processes and perhaps doubling or trebling the cost of the treatment so if the additional processes or equipment impinge on the cargo space), but the cost of onshore treatment would increase only fractionally. At higher levels of treatment the cost advantage of onshore treatment is substantially greater (Table VI.D-3). This cost partitioning is also the source of some of onshore treatment's greater adaptability: treatment processes and equipment can be substantially modified, updated, augmented or even largely replaced as experience dictates, without greatly increasing the total cost of treatment.

Table VI.D-3. Changes in the ratio of total shipboard to onshore costs as the spending on treatment increases.

Increase in spending on treatment processes and equipment	Ratio of total shipboard costs to total onshore costs in: California	United States
1x (no increase)	2.54	1.46
2x	4.79	2.63
3x	6.80	3.60
5x	10.20	5.08
10x	16.36	7.37

E. Potential Effectiveness of Onshore Treatment in Removing, Killing or Inactivating Organisms

Table VI.E-1 show the allowable concentrations in different organism categories for several ballast water discharge standards, which span the range of proposed requirements.[13] Table VI.E-

[13] The standards also include public health protective limits for three indicator bacteria species or groups (toxicogenic *V. cholerae*, *E. coli* and intestinal enterococci), but since there are no data available on the mean concentration of these indicator bacteria in untreated, unexchanged ballast water on which to base an analysis, they are not treated further in this section.

2 provides statistics on organism concentrations measured in unexchanged, untreated ballast water at the ends of voyages (IMO 2003).

Table VI.E-1. Ballast water discharge standards for four organism classes.

	>50 µm per m^3	10-50 µm per ml	Bacteria per ml	Viruses per ml
US Negotiating Position	0.01	0.01	–	–
IMO D2	10	10	–	–
USCG Phase 1	10	10	–	–
USCG Phase 2	0.01	0.01	10	100
California Interim	no detectable	0.01	10	100
California Final	no detectable	no detectable	no detectable	no detectable

Table VI.E-2. Organism concentrations in untreated, unexchanged ballast water. Data from IMO (2003). The data are from vessels sampled in the relatively few port areas where researchers have been funded to do this type of work. The zooplankton fraction (collected with nets with mesh sizes of 55-80 µm) is considered to correspond approximately to organisms in the >50 µm size class, and the phytoplankton fraction (collected with sieves with mesh sizes of <10 µm or counted in unconcentrated samples) is considered to correspond approximately to organisms in the 10-50 µm size class. VLPs are virus-like particles.

	Zooplankton	Phytoplankton	Bacteria	VLPs
n (# of tanks sampled) =	**429**	**273**	**11**	**7**
	per m^3	**per ml**	**per ml**	**per ml**
maximum	172,000	49,716	1,900,000	14,900,000
mean	4,640	299	830,000	7,400,000
median	400	13.3	–	–
mode	100	0.001	–	–
minimum	0	0.001	240,000	600,000

Table VI.E-3 shows the log reductions from the maximum, mean, median and modal concentrations represented by several of the discharge standards. Relative to the mean concentrations in untreated ballast water, the IMO D2 and USCG Phase 1 standards require a 2.7 log reduction in the concentration of organisms in the >50 µm class and a 1.5 log reduction in the 10-50 µm class; with no overall reduction for bacteria or viruses. The USCG Phase 2 standard requires a 5.7 log reduction in the >50 µm class and 4.5-4.9 log reductions in the 10-50 µm class, bacteria and viruses. The required reductions relative to median values are smaller.

Table VI.F-3. Log reductions required by different discharge standards.

	>50 µm per m^3	10-50 µm per ml	Bacteria per ml	Viruses per ml
USCG Negotiating Position				
reduction from maximum	7.2	6.7	no reduction	no reduction
reduction from mean	5.7	4.5	no reduction	no reduction
reduction from median	4.6	3.1	no reduction	no reduction
reduction from mode	4.0	no reduction	no reduction	no reduction
IMO D2; and USCG Phase 1				
reduction from maximum	4.2	3.7	no reduction	no reduction
reduction from mean	2.7	1.5	no reduction	no reduction
reduction from median	1.6	0.1	no reduction	no reduction
reduction from mode	1.0	no reduction	no reduction	no reduction
USCG Phase 2; and California Interim (except for >50 µm)				
reduction from maximum	7.2	6.7	5.3	5.2
reduction from mean	5.7	4.5	4.9	4.9
reduction from median	4.6	3.1	no data	no data
reduction from mode	4.0	no reduction	no data	no data

With regard to what can be achieved by onshore treatment, US EPA requires that drinking water treatment systems be capable of at least 3-5 log reductions in *Giardia*[14] and 4-6 log reductions in viruses, depending on the quality of the source water (US EPA 1991). Several common drinking water filtration technologies are capable of 3-4 log reductions in protists and bacteria and 2-4 log reductions in viruses (see Tables A1-8 to A1-10 in Appendix 1).

Membrane filtration technologies are capable of greater reductions (>4-6 log). In many of the membrane filtration assessments the remaining organism concentrations were below detection limits, and some documents describe these filters as “absolute barriers” that achieve “complete removal” of protozoans (by microfiltration—US EPA 1997b; LeChevallier & Au 2004; or by ultrafiltration—WHO 2008), of bacteria (by ultrafiltration—WHO 2008; or by nanofiltration—US EPA 1997b), and of viruses (by nanofiltration—US EPA 1997b; NESC 1999; WHO 2008). Although in practice these membrane systems might not serve as true "absolute" barriers (e.g. due to pinpoint failures over the course of operations), if they are operated and maintained as designed, they are probably capable of producing effluent in which no organisms would be detected by a ballast water compliance monitoring program.

[14] A protozoan with a flattened, pear-shaped active form (trophozoite) measuring around 3 x 9 x 15 µm and an ellipsoid cyst averaging 10-14 µm long.

UV disinfection can achieve 2-3 log reductions in protozoans and 3-4 log reductions in bacteria and viruses (Tables A1-8 to A1-10 in Appendix 1). Disinfection with biocides can achieve at least 3-log reductions in *Giardia*, 3-6 log reductions in bacteria, and 3-4 log reductions in viruses with appropriate doses and contact times (Tables A1-8 to A1-10 in Appendix 1); higher doses or contact times might achieve even greater reductions). Filtration and disinfection are generally considered additive processes (US EPA 1991): that is, a filtration process that can produce a 3 log reduction, and a disinfection process that can produce a 2 log reduction, in sequential combination are presumed to produce a 5 log reduction.

Thus, even without a disinfection step, several common drinking water filtration technologies that could be used onshore are capable of achieving the 1.5-2.7 log reductions from mean ballast water concentrations needed to meet the IMO D2 and USCG Phase 1 standards. Several combinations of filtration plus a single disinfection process appear capable of achieving the 4.5-4.9 log reductions needed to meet the USCG Phase 2 and California Interim requirements for viruses, bacteria and organisms in the 10-50 µm size class, and probably also the 5.7 log reduction needed to meet the USCG Phase 2 standard for organisms >50 µm. Treating with one or more additional disinfection process could produce yet greater log reductions.[15] In comparison, in tests of type-approved shipboard treatment systems organisms in the >50 µm size class were reduced by at least 2.4-4.9 log, and organisms in the 10-50 µm size class by at least 1-3.8 log, depending on the treatment and the test conditions; bacterial counts were increased more often than they were reduced, and the tests provided no data on the effect on viruses (Table A1-11 in Appendix 1).

Some membrane filtration technologies that could be used in onshore plants have produced results of no detectable organisms in different organism classes. For example, the microfiltration unit that Brown and Caldwell (2008) included in the conceptual design for onshore treatment at the Port of Milwaukee would likely result in no detectable organisms in the effluent in both the >50 µm and 10-50 µm size classes (based on microfiltration results cited in US EPA 1997b and LeChevallier & Au 2004) . On the other hand, ultrafiltration or nanofiltration might be needed to leave no detectable bacteria or viruses in the filter effluent.

Summary and Recommendations

Principal limitations of available data and protocols

- Data are not sufficiently comparable to compare rigorously across ballast water treatment systems because standard protocols for testing ballast water treatment systems have been lacking, and the ETV protocols only partly fill this gap.

[15] Studies have shown that sequential combinations of some disinfectants produce reductions even greater than the sum of the disinfectants' reductions when examined separately (LeChevallier & Au 2004).

- No requirement exists to report failures in testing.

- The important size class of 2 to $\leq$ 10 µm previously has been ignored in developing guidelines and standards.

- There is a serious mismatch between "living" standards and the practical limitations of available protocols. Clear definitions and direct methods to enumerate viable organisms in the specified size classes at low concentrations are missing for some size classes and logistically problematic for all size classes, especially nonculturable bacteria, viruses, and resting stages of many other taxa.

- Data on the effectiveness of practices and technologies other than shipboard ballast water treatment systems are woefully inadequate because insufficient attention has been given to integrated sets of practices and technologies including (1) managing ballast uptake to reduce presence of invasives, (2) reducing invasion risk from ballast discharge through operational adjustments and changes in ship design to reduce or eliminate need for ballast water, (3) development of voyage-based risk assessments and / or HACCP principles, and (4) options for on-shore treatment.

With respect to on-shore treatment, we reach the following conclusions:

- Onshore treatment of ballast water is technically feasible and preliminary estimates suggest that it is at least as economically feasible as shipboard treatment.

- Onshore treatment would require less total capacity and fewer treatment systems than would reliance on shipboard systems.

- Constraints of shipboard treatment systems (e.g., limited space, treatment time and available power, lack of stability) are largely or entirely absent in onshore systems.

- The total cost of onshore treatment is estimated to be less than the total cost of shipboard treatment of equal effectiveness, especially if a high level of effectiveness is required.

- The effort and cost of monitoring and enforcement needed to achieve a given level of compliance is likely to be much less for a relatively small number of on-shore treatment plants compared to approximately 300 times as many mobile, transient and sometimes foreign-owned shipboard plants which are available for inspection by U.S. regulatory agencies only when in U.S. ports for short periods of time.

To overcome present limitations, we recommend that:

- Testing should be conducted by a party independent from the manufacturer with appropriate, established credentials, approved by EPA/USCG.

- Infectious viruses should not be included in standards for BTWSs until new technology becomes commercially available that reliably distinguishes infectious from non-infectious agents.

- Complete test results for ballast water treatment systems, including failures, be reported and considered in certification decisions.

- Testing protocols should be standardized and, ideally, applied across the full gradient of environmental conditions represented by the Earth's ports, and use natural sources of water, including natural salinity, DOC, etc.

- The 2<10um size class of organisms should be included in ballast water standards, and therefore in protocols to assess the performance of ballast water treatment systems.

- Testing protocols diverge from those recommended by the ETV report for the components highlighted in Table 4.

- Protocols be developed to identify suitable surrogate taxa and surrogate parameters (e.g., algal pigments, total adenylates, INT, DNA, RNA, enumeration of preserved organisms) to complement or replace metrics that are logistically difficult or infeasible for estimating directly the concentration of living organisms. Three sets of concerns lead to this recommendation: the impracticality and inaccuracy of some of the current protocols for estimating the concentration of living organisms; the inherent mismatch between the "living" standard and available technology; and the lack of protocols appropriate for compliance and enforcement testing. Potential candidate species and parameters will require careful calibration with natural populations of ballast water organisms before they can be used to evaluate BWTS performance, especially at the resolution needed of very low organism densities.

- Use of representative "indicator" taxa (toxic strains of *Vibrio cholerae*; *Escherichia coli*; intestinal enterococci) should continue to be used as a sound approach to assess BWTSs for effective removal of harmful bacteria. These estimates will be improved when reliable techniques become available to account for active, nonculturable cells as well as culturable cells.

- Laboratory bench (small scale) tests should be used as a sound first step in assessing BWTS performance because they enable controlled testing over a full range of environmental and biological conditions and help to identify limitations or critical flaws in the system design while minimizing logistical difficulties, expense, and risks. As a second step, tests should be conducted in mesocosms (intermediate scale) because they enable testing under more realistic conditions in checking treatment performance prior to full-scale, land-based testing.

- That EPA develop a phased approach that includes metrics appropriate for compliance monitoring and enforcement before standards or rules are adopted.

- Combinations of practices and technologies (e.g., ballasting practices to reduce the uptake of harmful organisms, deballasting practices and port procedures to reduce the probability of population establishment) be considered as potentially more effective and potentially more cost-effective approaches than reliance on only one ballast water treatment technology.

- Ship-specific risk assessments (based on the environment and organisms present in previous ports of call)be used to help prioritize the use of risk management practices and technologies, as well the targeting of compliance and enforcement efforts.

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EPA SAB Ballast Water Advisory

Subgroup 8

Section 6: Risk Assessment, Management and HACCP:

Potential application to ballast water management

I. Introduction

The purpose of this section is to explore the use of risk assessment to put strategies for treatment of ballast water into a probabilistic decision making process. The first section describes how ballast water treatment (BWT) could be put into a risk based framework The second section describes how a management tool originally developed for food safety, Hazard Analysis and Critical Control Point (HACCP) might be used for managing ballast water treatment.

II. Risk Assessment

A. Establishment of an invasive species.

The establishment of an invasive or an emergent disease is the joint probability of how often the invasive would be introduced, an initial population size to ensure reproduction and the probability that it would find a suitable environment for propagation. This joint probability is low for any one species or likely shipping event. However, a large number of species can be transported via ship and thousands of ships arrive at U. S. ports making the probability of an invasive or a new pathogen becoming established a substantial probability. Given that shipping is a major industrial activity and that it will continue indefinitely, even a small probability for each ship and for each species, will result in successful invasions. The goal of a BWT program is to lower that probability, especially for especially damaging species and pathogens. In order for a BWT to be successful the goals need to be specific and measureable and the operational context needs to be understood. First a model of the relationship between the number of organisms in ballast water and the likelihood of invasion-infection needs to be derived.

B. Probabilistic approach to deriving propagule pressure and invasion relationships

It is possible to derive relationships between the number of organisms with an invasive potential (propagules) and the probability of an invasion over a specified amount of time. Such a relationship is described by Figure 1A. It is assumed that the greater the number of propagules the greater the probability of the establishment of an invasive species or pathogen. In this instance it is assumed that the relationship is sigmoidal but a number of curves are possible and may be specific to the type of organism or environment. The solid line represents the central tendency of the relationship with the dashed lines representing confidence intervals. Note that the confidence intervals include a successful invasion even without propagule pressure from ballast water and also the likelihood of no invasion even with organisms escaping. After all, organisms can come from a variety of sources other than ballast water.

Figure 1B describes how to set targets for the number of organisms in ballast water. First a policy decision is made about an acceptable frequency of successful invasion over a specified amount of time. Reading across the graph to where this rate intersects with the concentration-response curve gives the numbers of organisms corresponding to the low, expected and high values. Trade-offs can then be made on the likelihood of success in meeting the specification and the costs of achieving the goal.

Although these graphs were drawn to express the relationship with one species of concern, similar plots may be derived for discharges with a large number of species. The greater the types of different species, the larger the probability of an invasion by at least one of them.

Having the data to derive such relationships allow decisions to be made in the context of specific relationships. It may be that several different methods may be used in order to achieve the specified rate of invasion. However, the graph also allows describing considerations such as “what does zero mean” into a probabilistic context.

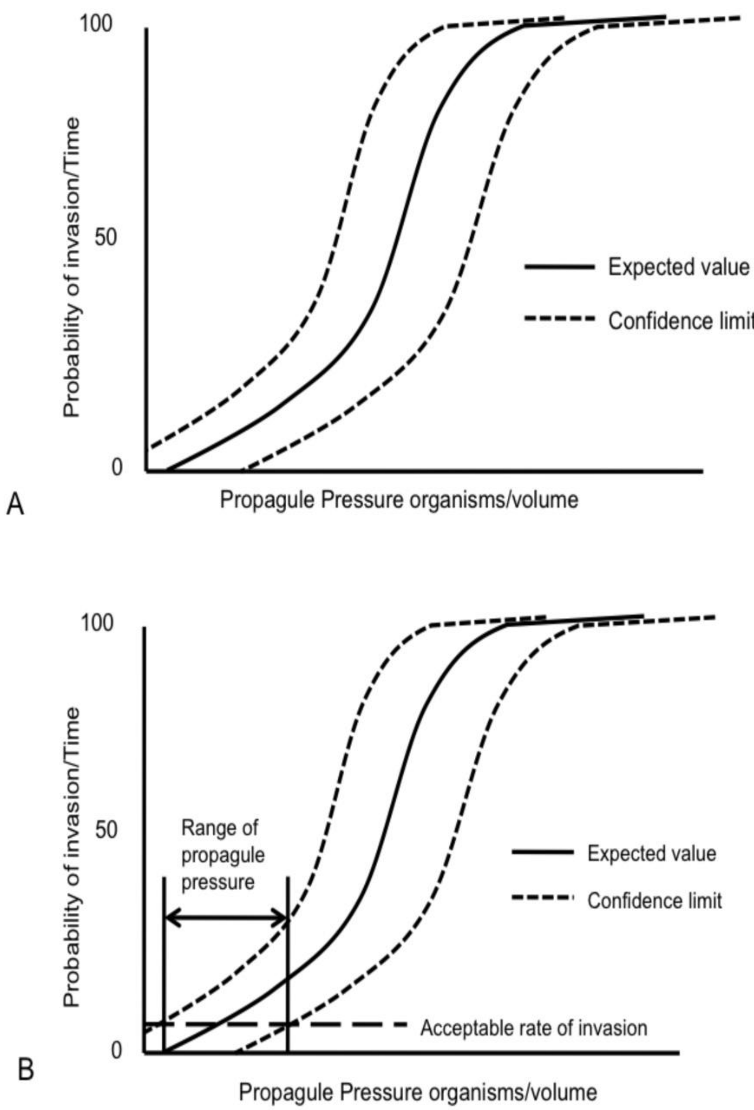

Figure 1. Relationship between propagule pressure (concentration) and the probability of an invasion by that species. Such a curve will allow the understanding of the concentration-probability relationship allowing a quantitative establishment of suitable goals for the reducing of potential invasives from ballast water. The confidence intervals around the expected probability provide a description of the uncertainty with the concentration-invasion relationship (Figure 1A). Once a level of probability is agreed upon the range of values of propagule pressures can be obtained that are likely to produce the result.

C. Ballast water treatment goals and the decision making, risk assessment context

In order to evaluate the various types of BWT it is important to understand how this fits into a decision-making context. This means that the management goal has to be clearly defined as in the above model. Additionally, the effectiveness of the treatment of the ballast water has to be evaluated within the context of a ship with cargo, human food and waste, and a number of organisms attached to the hull. There is also the possibility of human error in the treatment process that may lead to the escape of organisms or the release of toxic materials. Each of these items is covered below.

1. The goal, what does zero mean?

What does zero discharge of invasives mean as a goal since such a value is essentially not measureable. The volumes to be sampled are enormous, there are refugia from treatment within the ballast water tanks, and the discharge is into an environment with multiple sources of invasive species. There are operational definitions that may prove more useful in making a decision about ballast water treatment options.

For example, does zero mean that a discharge from a specific ship will not have any organisms that will colonize or infect a port environment for that one particular disinfection treatment and ship discharge. This is a very specific criterion but it is not necessarily protective. Measuring the effectiveness of each discharge event requires monitoring of the performance of the treatment and sampling of the discharge. Zero could also mean that the treatment technology or system will prevent the introduction of an invasive organism or disease to that port over a ten-year period? This is a very different criterion. In the second instance this is a performance-based requirement that gives the stated goal (no invasion or infection) over a specified time frame. Individual treatments on certain ships may fail but an overall system would ensure that invasives are eradicated early in a colonization event or that other methods would prevent propagation. These two goals are very different and would put the on-board or land based treatment options into specific contexts. In order to rank the various technologies and treatment systems the specific goals of the program need to be carefully defined.

There is also the question about specific goals for the protection of the port from pest invasives and pathogens. Are there specific requirements for each category of organism or is a combination approach to be attempted? Let us take pathogenic organisms as an example. In ballast water a large proportion of the organisms are likely to not be pathogenic, but the human welfare implications may (but not necessarily) be higher for the pathogenic organisms. Is the goal protection against human pathogens or those pathogens that may infect shellfish and fish populations, destroy important sea grass beds, or other segments of the ecological structure of the receiving port? Depending upon the specific policy goals a number of propagule pressure-infection relationships may need to be considered.

As the specifications for the treatment process are made it is also important to understand the context of a ship and its port facility. Ballast water would only be one of the potential sources of invasives and pathogens brought by ship.

2. Context of a cargo or tanker ship and the port facility

The ship has more that ballast water as a source of invasive species. Ships contain cargos of varied types, crew, food, human waste, and hull foiling organisms. The port facility may also have a variety of other ships using the facility that may be sources of invasives and pathogens. Understanding the efficacy of the treatment program needs to be placed into this broader context.

Cargo, food, human waste, and attached sea life will accompany ships and can be additional sources of invasives and pathogens. Cargo may contain insects, fungi, seeds and spores that may be released to the environment as the cargo is unloaded or transported. Food can be another source of materials if organisms are being transported. Human waste can be a source of pathogens, but can be disposed of using appropriate facilities. Fouling of the hull of the ship can be a source of invasives or pathogens depending upon the origin of the ship, route and time of transit, and the effectiveness of the anti-fouling paint and overall condition of the hull.

A confounding factor is that a number of other vessels will be using the same facilities and are sources of invasion. Fishing fleets and pleasure craft often take very long voyages and may be sources of invasives. These vessels also exist in different regulatory environments that may be more permissive in the transport of invasives. Although not directly affecting the infection potential of any single ship, these vessels can be confounding variables in the identification of the effectiveness of treatment or the identification of source. So although there may be zero propagules in the ballast water there may still be a probability of an invasion. Hence,the non-zero confidence interval in the initial example.

The risks due to the invasion are not the only risk to be considered in BWT. It will be important to assess the potential impacts of decontamination and the effluent upon the environment. Does disinfection for pathogens increase the risk to the environment from the treatment? The number of ships that use a port may also contribute to the trade-off. Decontamination activities that release an effluent with some residual toxicity may not pose an important risk to a facility that has a low volume, but may be important in a busier port. Some ports are very specialized. Port Valdez AK specializes in the shipping of crude oil and some oil product. Cherry Point WA is a port that currently receives crude from a limited number of sites to the refineries and bauxite for the smelter. Other facilities such as New Orleans or Seattle-Tacoma receive a variety of container ships and cargoes from across the world.

Shipboard emergencies, accidents and equipment failure should be considered in the risk analysis and decision making process. Weather conditions or shipboard emergencies may preclude the operation of shipboard treatment facilities. Operator error or equipment failure in the operation of the process may happen on shipboard or on-shore facilities just as it does in waste-treatment facilities. In parts of the United States hurricanes and northeasters can create damage to ships and on-shore equipment. No matter the type of treatment weather, accidents and equipment failure will occur and will introduce invasives to a port facility. Maximizing reliability of the process should be an important part of the risk analysis process.

3. BWT in an overall management program

Large-scale establishment of species from what appear to be multiple invasions have occurred. Kolar and Lodge (2001, 2002, Kolar 2004) have demonstrated that the Great Lakes are examples in which populations of European fish have been established from multiple invasion events. European Green Crab were established in San Francisco in the late 1980s and have spread north along the west coast (Behrens and Hunt 2000). Invasions take time, often decades, are often due to multiple releases, and are difficult to control once established. A BWT management strategy to decrease the rate of successful invasions should be part of an overall plan for the reduction of invasion events, monitoring, containment and eradication. Emphasis only on one aspect, the initial invasion event, is not likely to reduce the risk of invasives to an acceptable probability.

III. Risk Management and HACCP (Hazard Analysis and Critical Control Points)

A. What is HACCP?

HACCP is an acronym for **H**azard **A**nalysis and **C**ritical **C**ontrol **P**oint. HACCP was developed in the late 1950's to assure adequate food quality for the nascent NASA program. It was further developed by the Pillsbury Corporation, and ultimately codified by the National Advisory Committee on Microbiological Criteria for Foods in 1997. The ultimate framework consists of a seven-step sequence:

1. Conduct a hazard analysis.
2. Determine the critical control points (CCPs).
3. Establish critical limit(s).
4. Establish a system to monitor control of the CCPs.
5. Establish the corrective action to be taken when monitoring indicates that a particular CCP is not under control.
6. Establish procedures for verification to confirm that the HACCP system is working effectively.
7. Establish documentation concerning all procedures and records appropriate to these principles and their application.

In international trade, these principles are important parts of the international food safety protection system. The development of HACCP broke reliance on the use of testing of the final product as the key determinant of quality, but rather emphasized the importance of understanding and control of each step in a processing system (Sperber and Stier 2009).

Basic Definitions

<u>Hazard</u>

The hazard under HACCP is the constituent whose risk one is attempting to control.

Critical control points

A critical control point (defined in the food sector) is "any point in the chain of food production from raw materials to finished product where the loss of control could result in unacceptable food safety risk"(Unnevehr and Jensen 1996).

An important task in the HACCP process is to set performance criteria (critical limits) at each of the critical control points (CCPs). Based on the final desired quality, the minimum performance criteria for each of the CCPs is set, and the characteristics of each process that are readily measurable and necessary to assure performance are set. This may be done using experimentation, computational models or a combination of the two (Notermans, Gallhoff et al. 1994).

Application in Food and Water

HACCP has been applied in the food safety area for 50 years, and in the past decade guidelines and regulations in the US have been written that require an approved HACCP process in a number of applications. For example, FDA has developed a HACCP process applicable to the fish and shellfish industries (21 CFR 123). HACCP has also been widely adopted in the EU, Canada and a number of other developed and developing nations to food safety (Ropkins and Beck 2000).

Havelaar (1994) was one of the first to note that the drinking water supply/treatment and distribution chain has a formal analogy to the food supply/processing/transport/sale chain, and therefore that HACCP would be applicable. However, in effect, the development of the US surface water treatment rule under the Safe Drinking Water Act (40 CFR 141-142) and subsequent amendments incorporate a HACCP-like process. Under this framework, an implicitly acceptable level of viruses and protozoa in treated water was defined. Based on this, specific processes operated under certain conditions (e.g. Filter effluent turbidity for granular filters) were "credited" with certain removal efficiencies, and a sufficient number of removal credits needed to be in place depending on an initial program of monitoring of the microbial quality of the supply itself. This approach (of a regulation by treatment technique) is chosen when it is not "economically or technically feasible to set an MCL" (maximum concentration level) (Safe Drinking Water Act section 1412(b)(7)(A)).

B. How HACCP Might Be Applied in the Ballast Water Context

The HACCP approach might be applied in the context of ballast water via the following approach:

- Enumerate critical control points (which might include each particular treatment process as well as the method and type of intake water used itself)
- Determine the needed logs reduction in totality of the entire treatment system given the nature of the intake water (to achieve IMO, IMO*10, etc.), and allocate these reductions amongst individual treatment processes.

- Given criteria in the discharged treated ballast water (e.g. IMO or IMO*10, etc), determine the minimum performance criteria for each treatment process, as well as criteria that determine whether or not particular intake water might be suitable. Note that these performance criteria should be based on easily measurable parameters that can be used for operational control. Research may be needed to determine relationships <u>for each process</u> between such surrogate parameters and removal of each of the IMO size classes of organisms.
- A given ship having a set of processes with designed removal credits would only be allowed to take in ballast water that does not exceed the capacity of the controlled process train to meet the IMO criteria under the controlled operation.
- A QA process needs to be set up for periodic validation and auditing (for example by a 3rd party organization), and an operational procedure needs to be developed indicating what corrective action is to be taken for a particular installed process should a surrogate parameter be outside acceptable limits (this might be holding for additional time, recirculating for additional treatment, or some other measure).

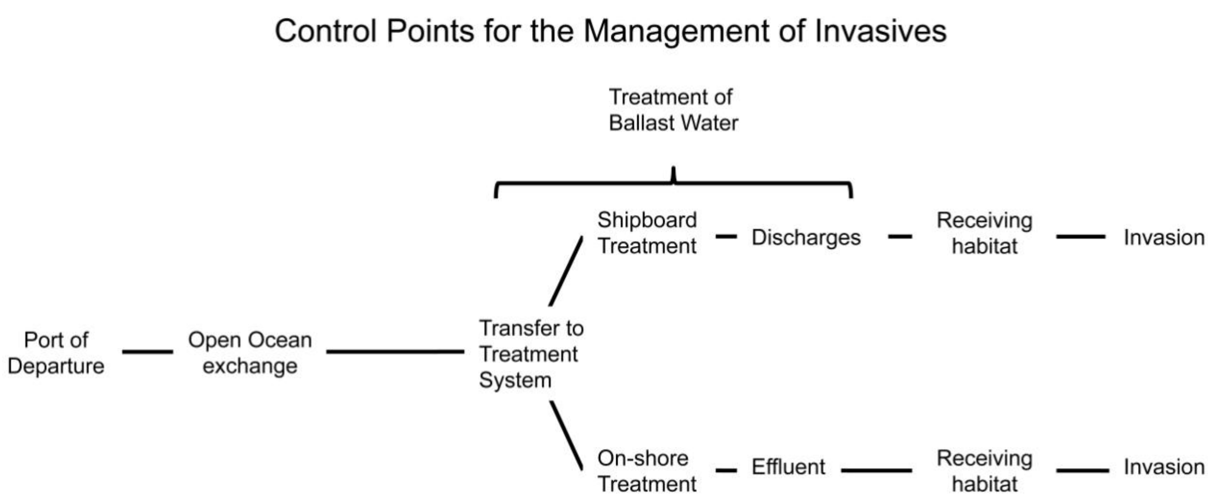

Figure 2. Some control points for the control of invasives. Each of the processes may have imbedded control points.

Control points also could be identified for the various steps in the transfer of an invasive species to a new habitat. This is illustrated in Figure 2.
The port of origin would contribute the source of propagules to the ballast water. Known hazards from particular ports could be identified and the protocol for the control process modified for those ports.

Open ocean (or water) exchange is a means of reducing the number of propagules from the original port. Due to sea conditions or other factors it may not be possible to have an exchange. The control process may require modification to allow for this contingency.

Next there is as transfer to the treatment system. If there is on-board treatment the piping and pumping will be contained on the ship. In the case of on shore treatment there will be connections to the facility and pumping the ballast off ship. For both types of treatment multiple control points can be identified (see above) that can be part of the HACCP process.

One of the differences in on-board and on shore treatment will be the release of the treated water to the environment. The ballast water treatment facility for the Port of Valdez is regulated by a NPDES permit as an effluent. A specific discharge site is identified and the concentrations of contaminants specified in the permit. On-board systems will discharge at the site of the ship and it is not clear what kinds of sampling and other specifications are to be placed on this material. In both categories of treatment the HACCP process could be implemented.

Likely outside of an engineering based HACCP but part of an overall strategy is the consideration of the receiving waters for the ballast water and the types of habitat. Receiving habitats that are similar to those of the original port are likely to provide more opportunity for the establishment of an invasive species or pathogen. This information may be useful in establishing a site-specific treatment recommendation. These habitats could also be monitored as part of an overall plan for reducing the likelihood of successful invasion.

IV. Citations

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